THE UNIVERSITY OF MICHIGAN
COLLEGE OF ENGINEERING
Department of Mechanical Engineering

Student Project Reports

INVESTIGATION OF DESIGN MEANS FOR HOME LAUNDRY APPLIANCES

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COMPUTER SIMULATION OF THE TRANSIENT-STATE OF VELOCITY EXTRACTION DRYING EQUIPMENT

Basil G. Kaskaras

1. Introduction

This work represents an attempt to complete a computer program that will simulate the operation of a Whirlpool washer dryer laundry appliance. A successful simulation program will enable the elimination of costly prototype testing. The program at hand is flexible enough to allow the programming of different configurations of the components that make up the system. My task was to evaluate the work already in existence, establish the validity of the steady-state solution, and proceed into the transient-state operation of the system, (Fig. 1).

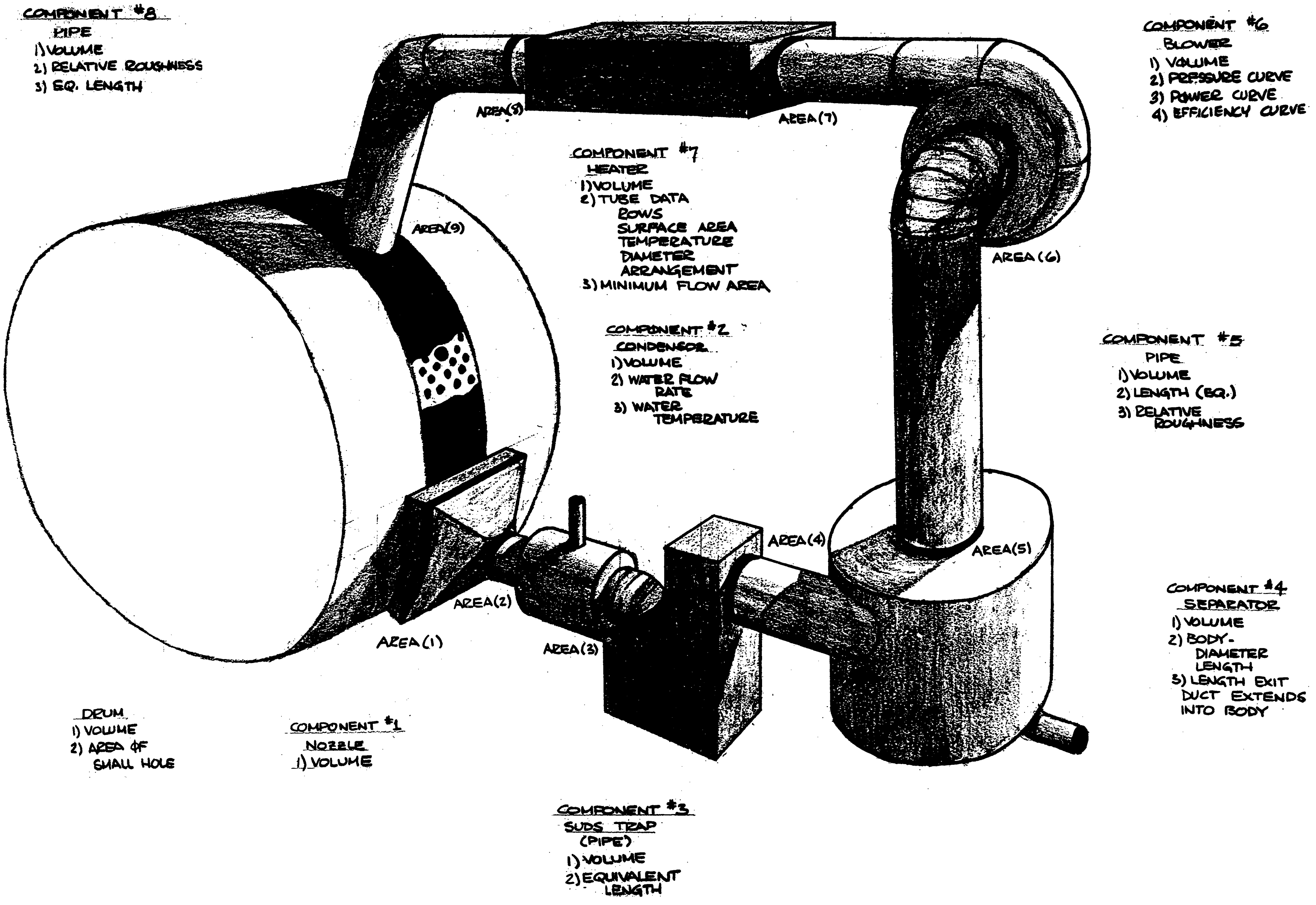

Fig. 1. Example system.

2. Simulation Method

In writing a program that will simulate a complicated system, care must be taken to make the program general enough to allow for future modifications. The program at hand is of a general nature. It is based on the following logic: suppose that the system is working at an initial level of operation (steady state) at time equal to zero, as defined by the physical factors affecting the total performance, such as geometry of the components, fluid medium characteristics, and other parameters. This is the instant corresponding to the starting of the machine. Suppose now that over a period of time following zero time an external excitation occurs, such as an instantaneous decrease in the quantity of fluid flow. This may be due to a decrease of the inflow nozzle area at the perforated plate location, caused by the turning around of the clothes in the drum. This decrease in fluid flow will affect the system, causing a decrease in the power and efficiency of the blower and a pressure rise across this same component. It will similarly affect all other components of the machine (see Ref. 8).

Any excitation in the drum, therefore, causes a sweeping change in the system. This change proceeds from component to component (starting with the component immediately connected to the drum, such as the nozzle in Fig. 1, and ending with the one just before reentrance into the drum, such as the heater in Fig. 1) in small time intervals until it has affected the whole system. At this point, the system has reached a second steady state of operation that is certainly different than that at time zero.

We see then that the system goes through a steady-transient-steady sequence of states over time. The exact nature of the transient response is not known.

It may have any of the forms shown in Fig. 2 or any other. Knowledge of this exact nature, however, is not necessary for the purposes of this computer program although it certainly is desirable. To simulate this transient state, an approximation method has been devised.[8]

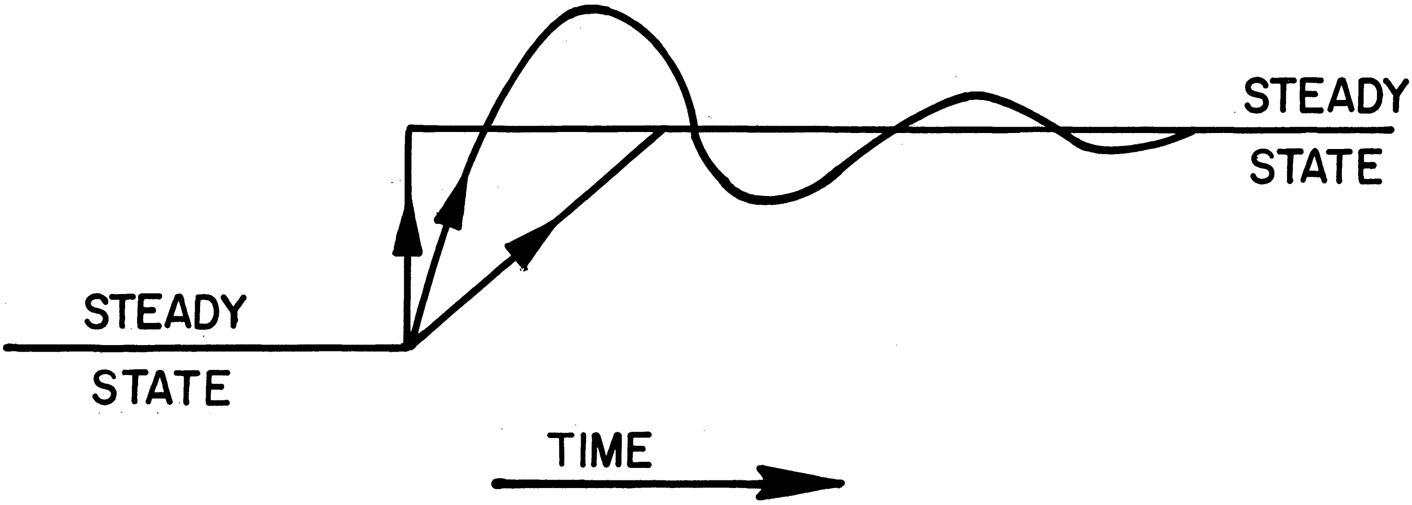

Fig. 2. Steady-~~transient~~ steady-state representation curve.

It is understood that any subsequent excitation will result in another transient state followed by another steady state, and so on, for as long as the system is working. This is the time it takes to dry the clothes. Thus the overall transient state of the system is approximated by determining the conditions in the system at subsequent instants of time as affected by the turning around of the clothes in the drum that cover or uncover larger or smaller portions of the perforated plate area at these subsequent time instants.

3. Work Previously Compiled and Present Effort

At the start of this project, a great deal of analytical and programming material was already available, having been compiled by former graduate students, D. Lane, V. Wedeven, and J. Robinson (see U of M student project reports 07494-2-P and 07494-3-P). The outcome of that work was a quite well-shaped computer program.

In the beginning of the present effort, the program was fed into the computer and compilation was achieved along with some initial calculations that led to a solution for the steady-state operation of the system. Obviously, there was no card punch error and the program was in accordance with the computer language (MAD) requirements. I began by making an evaluation of the flow diagram and rechecking the analytical work.

The flow diagram was judged to be good even though it could be written differently. However, such an effort was considered to be of no real value as it would lead only to neatness not simplicity. The system simulated by it is too complicated to be described by a simple procedure.

A very general flow diagram is shown in Fig. 3 (for a more detailed diagram see Ref. 8). In Fig. 3, the box calling for the determination of a new perforated plate area clearly indicates the need for another computer program which will provide the present computer program with a new inlet area at each subsequent instant of time. (For such a program see Robert Rice's report.)

Equation errors, found by checking the analytical work, may be due to three factors: errors due to lack of care in transferring from the literature to the program, derivation errors, and errors due to unit conversion factors. All three types of errors were encountered in this program at various points and corrected. Only that part of the theoretical work that was found to be incorrect appears below, superceding the work done by the previously mentioned students. That part of the work that checked correctly with their work will not be repeated here as it can be located in their reports.

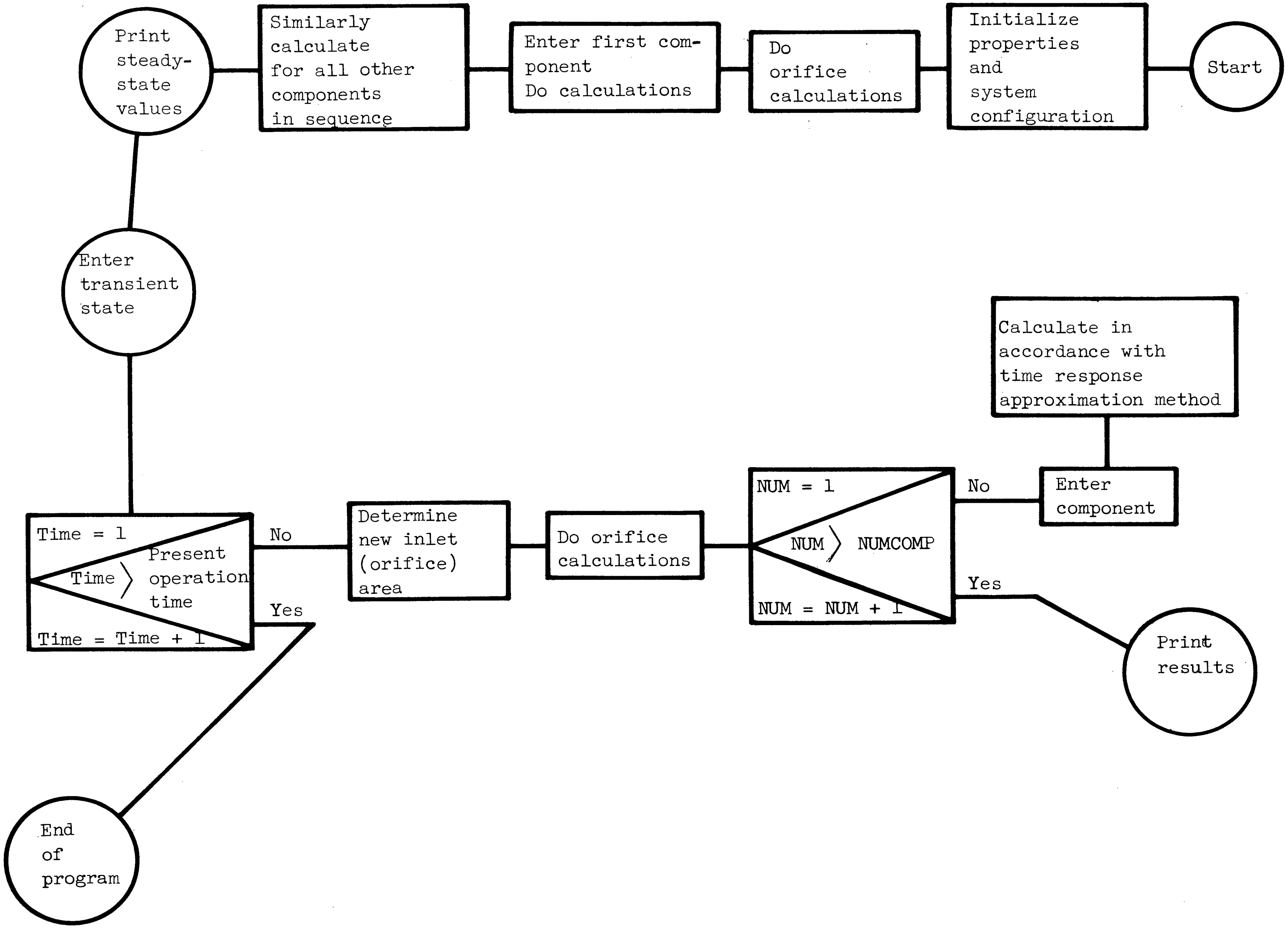

Fig. 3. Flow diagram.

4. Analytical Study

A. PIPES

Adiabatic flow with friction in pipes is considered. Gas flow through a pipe or constant area duct is analyzed subject to the following assumptions:

1. Perfect gas (constant specific heats).
2. Steady one-dimensional flow.
3. Adiabatic flow (no heat transfer through walls).
4. Constant friction factor over length of pipe.
5. Effective pipe diameter D is four times hydraulic radius (cross-sectioned area divided by perimeter).
6. Elevation changes are unimportant as compared with friction effects.
7. No work added to or extracted from the flow.

The controlling equations are continuity, energy, momentum, and the equation of state. The momentum equation must include the effects of wall shear stress and is conveniently written for a segment of duct of length δx (Fig. 4):

$$pA - (p + \frac{dp}{dx}\delta x)\,A - T_0 nD\delta x = pVA(V + \frac{du}{dx}\delta x - V)$$

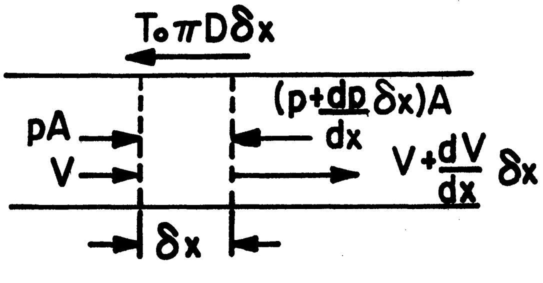

Fig. 4. Segment of duct of length δ_x.

Upon simplification

$$dp + \frac{4\,T_o}{D}\,dx + \rho V dV = 0 \qquad (P.\ 1)$$

Since $T_o = \rho f V^2/8$, where f is the Darcy-Weisbach friction factor,

$$dp + \frac{f\rho V^2}{2D}\,dx + \rho V dV = 0 \qquad (P.\ 2)$$

For constant f, or average value over the length of reach, this equation may be transformed into an equation for x as a function of Mach number. Dividing Eq. (P. 2) by p,

$$\frac{dp}{p} + \frac{f}{2D}\,\frac{\rho V^2}{p}\,dx + \frac{\rho V}{p}\,dV = 0 \qquad (P.\ 3)$$

each term is now developed in terms of M. By definition $M = V/c$

$$V^2 = M^2\,\frac{kp}{\rho} \qquad (P.\ 4)$$

or

$$\frac{\rho V^2}{p} = kM^2 \qquad (P.\ 5)$$

for the middle term of the momentum equation. By rearranging Eq. (P. 4)

$$\frac{\rho V}{p}\,dV = kM^2\,\frac{dV}{V} \qquad (P.\ 6)$$

Now to express dV/V in terms of M, from the energy equation

$$h_o = h + \frac{V^2}{2} = c_pT + \frac{V^2}{2} \qquad (P.\ 7)$$

Differentiating

$$c_p dT + VdV = 0 \qquad \text{(P. 8)}$$

By dividing through by $V^2 = M^2kRT$

$$\frac{c_p}{R}\frac{1}{kM^2}\frac{dT}{T} + \frac{dV}{V} = 0$$

Since

$$\frac{c_p}{R} = \frac{k}{k-1}$$

get

$$\frac{dT}{T} = -M^2(k-1)\frac{dV}{V} \qquad \text{(P. 9)}$$

Differentiating $V^2 = M^2kRT$ and dividing by the equation,

$$2\frac{dV}{V} = 2\frac{dM}{M} + \frac{dT}{T} \qquad \text{(P. 10)}$$

Eliminating dT/T in Eqs. (P. 9) and (P. 10) and simplifying

$$\frac{dV}{V} = \frac{\frac{dM}{M}}{(\frac{k-1}{2})M^2+1} \qquad \text{(P. 11)}$$

which permits elimination of dV/V from Eq. (P. 6) yielding

$$\frac{\rho V}{V} dV = \frac{kMdM}{(\frac{k-1}{2})M^2+1} \qquad \text{(P. 12)}$$

And finally, to express dp/p in terms of M, from = = ρRT and $G = \rho V$

$$pV = GRT \qquad \text{(P. 13)}$$

By differentiation

$$\frac{dp}{p} = \frac{dT}{T} - \frac{dV}{V}$$

Equations (P. 9) and (P. 11) are used to eliminate dT/T and dV/V:

$$\frac{dp}{p} = -\frac{(k-1)M^2+1}{\left(\frac{k-1}{2}\right)M^2+1}\frac{dM}{M} \qquad \text{(P. 14)}$$

Equations (P. 5), (P. 12), and (P. 14) are now substituted into the momentum equation (P. 3). After rearranging,

$$\frac{f}{D}\,dx = \frac{2(1-M^2)}{kM^3\left[\left(\frac{k-1}{2}\right)M^2+1\right]}\,dM$$

$$= \frac{2}{k}\frac{dM}{M^3} - \frac{k+1}{k}\frac{dM}{M\left[\left(\frac{k-1}{2}\right)M^2+1\right]} \qquad \text{(P. 15)}$$

which may be integrated directly. By using the limits x = 0, M = M_o, x = L, M = M,

$$\frac{fL}{D} = -\frac{1}{kM^2}\Bigg]_{M_o}^{M} - \frac{k+1}{2k}\,\ell n\,\frac{M^2}{\left(\frac{k-1}{2}\right)M^2+1} \qquad \text{(P. 16)}$$

or,

$$\frac{fL}{D} = \frac{1}{k}\left(\frac{1}{M_o^{\,2}} - \frac{1}{M^2}\right) + \frac{k+1}{2k}\,\ell n\left[\left(\frac{M_o}{M}\right)^2\frac{(k-1)M^2+2}{(k-1)M_o^{\,2}+2}\right] \qquad \text{(P. 17)}$$

From Ref. 4, p. 224

$$f\,\frac{L}{D}\frac{V^2}{2g} = k\,\frac{V^2}{2g}$$

Therefore

$$L = \frac{(kk)(D)}{f} \qquad \text{(P. 18)}$$

For computer adaptation of Eq. (P. 17), in accordance with the half-interval technique, the equation becomes

$$[\text{DLMAC}]\ \frac{fL}{D} = \frac{1}{k}\left(\frac{1}{M_o^2} - \frac{1}{M^2}\right) + \frac{k+1}{2k}\ \ell n\left[\left(\frac{M_o}{M}\right)^2 \frac{(k-1)M^2+2}{(k-1)M_o^2+2}\right] \qquad (\text{P. } 19)$$

It is therefore possible to calculate the downstream pressure p_2 using the relation

$$p_2 = \frac{\dot{m}_2}{M_2}\left(\frac{RT_{o2}}{k(1+\frac{k-1}{2})M_2^2}\right)^{1/2} \qquad (\text{P. } 20)$$

where,

$\dot{m}_2$ = downstream mass rate of flow

T_{o_2} = stagnation temperature

M_2 = downstream Mach number

R = perfect gas constant

k = specific heat ratio

The following relations also hold:

$$T_2 = \frac{T_{o_2}}{1+\frac{k-1}{2}M^2} \qquad (\text{P. } 21)$$

$$\rho_2 = \frac{P_2}{RT_2} \qquad (\text{P. } 22)$$

$$P_{o_2} = P_2(1+\frac{k-1}{2}M_2^2)^{k/k-1} \qquad (\text{P. } 23)$$

$$V_2 = c_2 M_2 \qquad (\text{P. } 24)$$

where

$$c_2 = \sqrt{kgRT_2}\ . \qquad (\text{P. } 25)$$

On the other hand, for rough pipes the following equations apply

$$\frac{1}{\sqrt{f}} = 1.74 + 2 \log_{10} \frac{r_o}{k} \qquad \text{(P. 26)}$$

$$\frac{fL}{D} = \frac{1}{kM_1^2} [1 - (\frac{P_2}{P_1})^2 - 2 \log_e \frac{P_1}{P_2} \qquad \text{(P. 27)}$$

while for smooth tubes

$$f = 0.00357 + \frac{0.3052}{(2 \text{ Rey})^{0.35}} \qquad \text{(P. 28)}$$

$$\frac{fkL}{D} = (\frac{1}{M^2} - 1) + \frac{k+1}{2} \ln \frac{(k+1)M^2}{2[1+\frac{k-1}{2}M^2]} \qquad \text{(P. 29)}$$

where

D = hydraulic diameter

f = friction factor

B. HEATERS

For turbulent flow ($\text{Rey} > 6000$) over banks of tubes regardless of whether they are staggered or arranged in-line, the equation

$$\frac{h_c D_o}{k_f} = 0.33 \, C_H \left(\frac{G_{max} D_o}{\mu_f}\right)^{0.6} Pr^{0.3} \qquad \text{(H.1)}$$

where

h_c = film coefficient of heat transfer

D_o = outside diameter

k_f = fluid thermal conductivity

P_r = Prandtl number

μ_f = fluid viscosity

G_{max} = mass velocity at minimum area, (ℓbm/hr-ft^2)

holds in reality, provided that the tube bundle has ten or more transverse rows. The values of the empirical coefficient c_H depend on the tube arrangement and the Reynolds number.

The frictional pressure drop in ℓbm/ft^2 for flow over a bank of tubes is given by

$$\Delta p = \frac{f' G_{max}^2 N}{\rho (2.09 \times 10^8)} \left(\frac{\mu_s}{\mu_b}\right)^{0.14} \qquad \text{(H. 2)}$$

where

ρ = mass density, ℓbm/ft^3

f' = empirical friction factor

N = number of transverse rows

μ_s = fluid viscosity of the stream

μ_b = fluid viscosity of the fluid at the wall

For staggered tube arrangements and Rey > 1000

$$f' = \left[0.25 + \frac{0.118}{\left(\frac{S_T - D_o}{D_o}\right)^{1.08}}\right] \left(\frac{G_{max} D_o}{\mu_b}\right)^{-0.16} \qquad \text{(H. 3)}$$

For in-line tube arrangements and Rey > 1000

$$f' = \left[0.044 + \frac{0.08\ S_L/D_o}{\left(\frac{S_T - D_o}{D_o}\right)^{0.43+1.13\ D_o/S_L}}\right] \left(\frac{G_{max} D_o}{\mu_b}\right)^{-0.15} \qquad \text{(H. 4)}$$

By definition, the following relations hold:

1. $N_{pr} = (\mu C_p / \kappa_f)$ = Prandtl number

2. $j_H = \left(\frac{hc}{C_p G}\right) N_{pr}^{2/3}$ = Colburn J factor

where

$$G = \frac{M}{A_c} = \frac{4M}{nD^2}$$

3. $\text{Rey} = \frac{DG}{\mu}$ = Reynolds number

4. $N_{nu} = \frac{hcD}{\kappa_f}$ = Nusselt number

5. $f = ((\Delta p/L)/(G^2/2g_c D\rho))$ = friction factor

where g_c = conversion factor = 32.17 (ft-ℓbm/lbf-sec^2)

$\frac{\Delta p}{L}$ = frictional pressure drop per unit length

For flow normal to banks of staggered tubes, $2000 < \text{Rey} < 3.2 \times 10^4$

$$j_H = 0.33\ \text{Rey}^{-0.4} \qquad \text{(H. 5)}$$

where the fluid properties are evaluated at the mean film temperature $T_M = 0.5(T_b + T_w)$.

For flow normal to banks of tubes in-line, $2000 < \text{Rey} < 3.2 \times 10^4$

$$j_H = 0.26\ \text{Rey}^{-0.4} \qquad \text{(H. 6)}$$

where the fluid properties are again evaluated at T_M.

For flow across staggered tubes, Rey > 1000, the friction factor is

$$f' = [1 + 0.470\ (x_T - 1)^{-1.08}]\ \text{Rey}^{-0.16} \qquad \text{(H. 7)}$$

where

$$X_T = \frac{\text{transverse pitch}}{\text{tube outside diameter}} = \frac{ST}{H_o DO(N)}$$

For flow across in-line tubes, Rey > 1000

$$f' = [0.176 + 0.32\ X_L(X_T-1)^{-n}]\ \text{Rey}^{-0.15} \qquad (H.\ 8)$$

where

$$X_L = \frac{\text{longitudinal pitch}}{\text{tube outside diameter}} = \frac{SL}{HDO(N)}$$

$$n = 0.43 + \frac{1.13}{X_L}$$

The definition of longitudinal and transverse pitch is illustrated in Fig. 5.

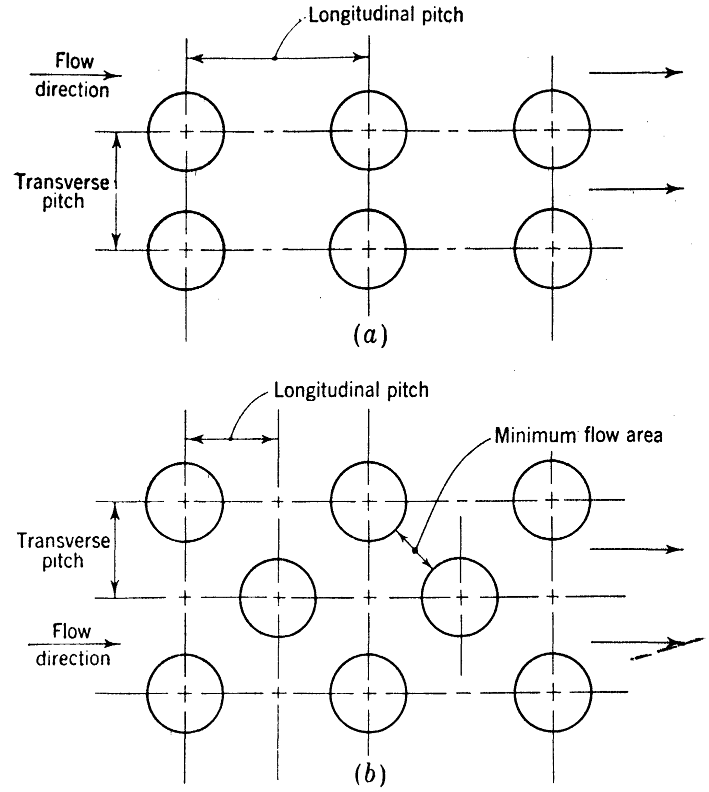

Fig. 5. Definition of longitudinal and transverse pitch (a) for tubes in-line and (b) for staggered-tube arrangement.

Since the Calrod heater actually used in the Whirlppol appliance under study can be represented by a staggered tube type of heat exchanger, the appropriate equations are used in the computer program.

5. Computer Program Subroutines

A. SOLVE SUBROUTINE

This subroutine is used to solve for the Mach number at a point if the following quantities are known at that point: stagnation temperature, stagnation pressure, area, and mass rate of flow. The following relations are known to be true:

$$c = \sqrt{\kappa R T_g} \qquad \text{(S. 1)}$$

$$M = \frac{V}{c} \qquad \text{(S. 2)}$$

$$P_o = P\left(1 + \frac{k-1}{2} M^2\right)^{(k/k-1)} \qquad \text{(S. 3)}$$

$$T_o = T\left(1 + \frac{k-1}{2} M^2\right) \qquad \text{(S. 4)}$$

$$p = \rho RT \qquad \text{(S. 5)}$$

$$\dot{m} = \rho VA \qquad \text{(S. 6)}$$

Equation (S. 3) gives:

$$\begin{aligned} P_o &= P\left(1 + \frac{k-1}{2} M^2\right)^{(k/k-1)} = \rho RT\left(1 + \frac{k-1}{2} M^2\right)^{(k/k-1)} \\ &= \frac{\dot{m}}{VA} RT\left(1 + \frac{k-1}{2} M^2\right)^{(k/k-1)} \\ &= \frac{\dot{m}}{AM\sqrt{kRTg}} RT\left(1 + \frac{k-1}{2} M^2\right)^{(k/k-1)} \end{aligned}$$

$$= \frac{\dot{m}}{AM} \sqrt{\frac{R}{kg}} \sqrt{\frac{T_o}{(1 + \frac{k-1}{2}M^2)}} (1 + \frac{k-1}{2} M^2)^{(k/k-1)}$$

$$= \frac{\dot{m}}{AM} \sqrt{\frac{RT_o}{k_g}} (1 + \frac{k-1}{2} M^2)^{((k+1)/2(k-1))} \qquad (S.\ 7)$$

since

$$\frac{k}{k-1} - \frac{1}{2} = \frac{k+1}{2(k-1)}$$

where

$\dot{m}$ = mass rate of flow

A = area

V = velocity

ρ = density

R = gas constant

T = temperature

T_o = stagnation temperature

P_o = stagnation pressure

M = Mach number

k = specific heat ratio

For listing, see the Appendix. This function also incorporates the half-interval approximation technique as explained in this report.

B. CALMAC SUBROUTINE

The derivation of this function is given here for clarification purposes. This subroutine is used to solve for the Mach number at a point if the following quantities are known at that point: stagnation temperature, pressure, area, and mass rate of flow. The following relations hold:

$$c = \sqrt{kRT_g} \tag{C. 1}$$

$$M = \frac{V}{c} \tag{C. 2}$$

$$T_o = T(1 + \frac{k-1}{2} M^2) \tag{C. 3}$$

$$p = \rho RT \tag{C. 4}$$

$$\dot{m} = \rho VA \tag{C. 5}$$

From solve subroutine 1 have:

$$P_o = P(1 + \frac{k-1}{2} M^2)^{(k/k-1)} = \frac{\dot{m}}{AM} \sqrt{\frac{RT_o}{k_g}} (1 + \frac{k-1}{2} M^2)^{((k+1)/(2(k-1)))}$$

Consequently,

$$P = \frac{\dot{m}}{AM} \sqrt{\frac{RT_o}{k_g}} (1 + \frac{k-1}{2} M^2)^{-1/2}$$
$$= \frac{\dot{m}}{AM} \sqrt{\frac{RT_o}{k_g}} \frac{1}{\sqrt{1 + \frac{k-1}{2} M^2}}$$

Squaring both sides and transposing, get

$$[1 + \frac{k-1}{2} M^2] M^2 = (\frac{\dot{m}}{AP})^2 \frac{RT_o}{k_g}$$

or

$$(\frac{k-1}{2}) M^4 + M^2 - (\frac{\dot{m}}{AP})^2 \frac{RT_o}{kg} = 0 \tag{C. 6}$$

where the symbols are the same with those used in the SOLVE function.

6. Approximation Methods

The large number of idealized equations used in this program will, of course, lead into results that are not close to actual test data within the required accuracy. Consequently, approximation techniques are needed that will compel the program to give accurate results. The half-interval technique is usable here when one of the quantities involved in an equation is unknown and is to be calculated so that the equation is true within specified limits of accuracy. The solution is found by means of an iteration looping. Example:

Assume that we have the equation $A = B$ where one of the factors b of the right member B is unknown. Also assume that for our purposes the equal sign of the equation must hold true within 2% of accuracy, that is,

$$.98\ A = B$$

and b is known to be a number within the interval $X \ldots Y$. Then by setting

$$b\ (1) = X$$

$$b(2) = Y$$

$$b\ (3) = \frac{X + Y}{2}$$

the equation $.98\ A = B$ will be satisfied after a certain number of iterations. In this program, approximately ten such iterations are being used.

For an actual application of the above approximation procedure, see the SOLVE function in the Appendix.

7. Need For Experimental Data

Certainly experimental data should be made available for purposes of comparison with the program output. At the present time, the lack of such data is not a critical factor since the program output values are undoubtedly incorrect. In the future, however, convergence of the program output within reasonable values will make the necessity for experimental data increasingly obvious. Such data will afford a check at each instant of time at every location of interest within the system.

8. Conclusion

This program presents the same hazard that all such large programs present. That is, since the result of each equation is used in a large number of other equations for simultaneous solution of the system, in a chain reaction manner, an error at one point may later become highly magnified, thereby making the program incorrect and futile. Consequently, when the small deviation from reality of the idealized equations used in the program is taken into account, it is not expected that the program will approach accurate values. Therefore, it is necessary to use approximation techniques that will compel the program to produce results that are close to experimental values within tolerable limits of accuracy. The degree of agreement of the computer program results with experimental values will dictate whether or not the program will (1) eliminate costly prototype testing, (2) simply give an indication of what is happening in the system, or (3) be of no value at all.

9. Term Dictionary (For a Complete Listing See Ref. 8).

ALPAM - parameter used in pipe calculations

DFRI - parameter used in pipe steady-state analysis

DLMAC - error measure in pipe Mach number calculations

N - location in system between two consecutive components

SCONC - parameter in SOLVE function

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INVESTIGATION OF CLEANING METHODS FOR HOME DISHWASHERS

James C. McCall

1. Introduction

It would be advantageous if a dishwasher could be built that might be smaller, cost less, require less power, handle more materials, clean better, clean faster, or clean in less time, or accomplish many of the above. This project involved the investigation of cleaning methods that would hopefully be better in some of the above aspects.

The following paper is a presentation of all the work that led to the design, construction, and operation of a water impact dishwasher that could handle solid "abrasives" to create more mechanical scrubbing action. All the work is presented, hoping it may be of benefit to the reader.

At the beginning of the project it was decided that a thorough investigation be done on all present-day cleaning methods. Later one would be picked to be built and tested, but at no time would limitations of power, cost, and size be considered in the investigation or selection of any cleaning method. The feasibility of building a successful dishwasher using each type of cleaning method was also considered. On the basis of feasibility, water impact, emulsion, and solvent dishwashers were proposed for selection of one to be built and tested. The water impact system with the additive was selected.

It should be realized that most information available on cleaning refers to assembly-line parts cleaning. The information presented here will be consistent with that available, but these methods are certainly adaptable to cleaning dishes.

2. Problem

The problem chosen for this project was to study all cleaning methods that might be useful for cleaning dishes and then select one to be built and tested. The dishwasher need not be conventional in any respect and it could conceivably clean only certain types of dishes with certain soils. This way the dishwasher could conceivably clean only pots and pans in a separate compartment that could eventually be incorporated with a conventional dishwasher. Cost, power, and size were not considered as factors since they could be handled at a later time if such further work is considered desirable or necessary. Only the ability to clean and the feasibility and practicality of building and testing one in the laboratory were considered.

3. Information on Cleaning Methods

A. IMPACT CLEANING

Impact cleaning includes any type of mechanical scrubbing action achieved by impact of particles and/or fluids. The conventional dishwasher is included in this, but its cleaning action is largely due to the chemical action of the detergent. Hence, it is more of a chemical cleaner than impact cleaner.

Impact cleaning is done with many abrasives including sand, steel grit, steel shot, mud, synthetic or artificial abrasives, rubber slugs, and sawdust. (15:144-151)* Fluids include air, steam, and water.

Sand is a good abrasive that can give a mild scrubbing action. When considering an impact system that uses a mechanical scrubbing action, one must be careful not to overrate the mechanical scrubbing action and assume that it will damage materials such as those found in kitchenware. Most sand blasters actually use an artificial abrasive that is much more abrasive than sand. Sand is used to clean delicate artwork and is almost the universal abrasive for glass, vitralite, china, etc. (15:132) To give glass a fine frosting, it is necessary to resort to steel grit. (15:132)

Vibratory finishing, included in impact cleaning, generally uses a barrel that contains an abrasive and the parts to be cleaned. Rotary and vibratory motion creates a scrubbing action that is good for ceramic and plastic parts. The vibratory motion is created by offset weights or shafts where the amplitude is controlled by the weight. Water can be added to create a more mild scrubbing action and chemical compounds can also be incorporated. (12:141-142)

B. SOLVENT CLEANING

Solvents are often used to clean parts either by a dip tank method or by a spray system similar to the type of action used in a dishwasher. Solvents can be used hot or cold and are often reclaimed by distillation.

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*This notation is used to refer to the reference in the bibliography found at the end of this paper. The first number refers to the reference number and the second number refers to the page number.

Many commercial solvents are available. Best known is probably perchlorethylene, used for dry cleaning. Other solvents include trichlorethylene, methyl chloroform, trichlorothrifluoroethane, methylene chloride, fluorinated hydrocarbons, petroleum solvents, and Dow Chlorethane.

A dirt-shearing action can be achieved by vertical agitation at 60-120 cycles per second with a five-minute normal cleaning action for some applications. (2:64) Solvent systems are used to clean clothes, metals, plastics, and other materials. Du Pont's Freon T-F is used in conjunction with ultrasonic dip baths to do precision cleaning of particles 1/40 the size of human hair for gyroscopes. It is nonflamable, nonexplosive, and virtually nontoxic. Its advantages include natural stability in resisting degradation, unlimited reuse of recovered solvent, and its ability to be combined with other solvents. (14:95) (For discussions on trichlorethylene, perchlorethylene, methyl chloroform, trichlorotrifluorethane, methylene chloride, and fluorinated hydrocarbons see 16:136 and the following pages.)

Solvents tend to be expensive, but the effects of high cost can be reduced by distillation reclaiming. With distillation reclaiming, the solvent is generally hot when used.

Petroleum solvents present a fire hazard and do not produce a high degree of cleaning. (16:137) The fire hazard makes petroleum solvents impractical for kitchen use.

Alkaline cleaning is in effect a detergent action. (16:137) Surface active agents are used to bolster the efficiency of a cleaner and reduce the need for high alkalknity. (1:97) Alkalies include metasilicates, pyrophosphates, nonionic and ionic synthetic detergents. (1:98) Contrary to popular belief, alkaline cleaners can be used on aluminum. (1:97)

Cold solvents have many advantages which are listed below: (13:58)

1. Equipment costs are lowered.

2. Contaminates that tend to set do not harden.

3. No time is needed to heat parts to temperature.

4. Design and installation are simplified.

5. Additives (wetting agents and rust preventives) that cannot withstand heat can be used.

6. Solvent breakdown is minimized.

7. Parts do not have to be cooled before handling.

C. EMULSION AND DIPHASE CLEANING

Emulsion and diphase cleaners are solvent cleaners. They are considered separately here since they are handled differently and react differently.

Emulsification occurs when a dilutent such as water is added to an emulsion concentrate. The two immisicible liquids are intimately combined as a stable solution in which the particle size of dispersed solvent phase varies from 1 to 10 microinch in diameter. Reduction of particle size during emulsification and maintenance of condition during the serviceable life of solution is governed by a surface-activating agent. (16:139)

There are three types of emulsion cleaners.

1. Emulsifiable Solvent (16:138). An emulsifiable solvent is a diluted or undiluted petroleum solvent. It is effective in removing tightly adherent and heavy soils. It is normally used in a room temperature immersion bath, followed by a hot rinse that removes the loosened soil, but leaves a thin oily film.

2. Stable Emulsion (16:138-139). In a stable emulsion the dilutent is water. Stable emulsions simultaneously remove water soluable and solvent soluable oils; however, they also leave thin oily residue. Stable emulsion cleaners may be used up to 180°F. Maximum effectiveness is achieved in spray systems, but it also performs well in soak-type cleaners. A stable emulsion has the ability to disperse a soil once it has been removed, thus preventing redeposition.

3. Diphase Cleaners (16:139). Diphase cleaners differ in that two distinct phases are present upon dilution. One is the solvent which may be the heavier or lighter fraction; the second is water. The solvent removes oils and wets the metal. The water dissolves water-soluble contaminates and wets mineral oils. Again a thin oily residue is left even after a hot rinse. Operating temperatures are limited by low-flash points.

Emulsifiable solvents and stable emulsion cleaners contain four ingredients (16:139):

1. Organic solvent - usually a hydrocarbon such as kerosene or naphtha.
2. Acid soap or fatty acid which serves as emulsifying agent.
3. Blending agent which serves as wetting agent, providing a homogeneous and stable mixture of solvent and emulsifying agent.
4. Surface activating agent to increase cleaning effectiveness.

D. VAPOR DEGREASING

Vapor degreasing is primarily used for the degreasing of metal parts by condensing a solvent vapor on the metal parts. Solvents with low boiling points could be used to clean dishes in a system that by its nature would reclaim the solvent by distillation.

Vapor degreasing systems require no mechanical action and can consist of systems that use the following phases:

1. Vapor
2. Warm liquid + vapor
3. Boiling liquid + warm liquid + vapor
4. Vapor + spray and vapor (16:136)

The advantages of vapor degreasing are:

1. Parts emerge dry.
2. It penetrates blind holes, etc.
3. Solvent cost is independent of soil removed due to redistillation.
4. System requires little space. (5:44)

Trichlorethylene ("tri") and perchlorethylene ("per") are commonly used for vapor degreasing but both require volatile stabilizers. Both dissolve a wide range of soils, such as greases, waxes, resins, tars, gums, and fats. They are inert to metal, have low toxicity, and are nonflamable and inexpensive. Their properties include low latent heat value (low distillation cost), chemical stability, and ability to support cavitation in ultrasonic degreasers. Perchlorethylene has a fairly high boiling point (parts emerge too hot to handle), but tri has a lower one. Tri needs an additive to remove water, and both must periodically be checked for acidity and oil content. Both can have a neutral or alkaline solution. (5:45-47)

The limitations of tri and per include the inability to remove hard caked-on soils. Some soils react with solvents and consequently must be removed beforehand. (5:50) The solvents may attack some plastics and the vapors that escape can be harmful if they come in contact with something hot. (9:129-130)

E. ULTRASONIC CLEANING

Ultrasonic cleaning is presently receiving much attention due to its ability to clean and sterilize. It removes soil from 10 micron to submicron range. (17:62) It is generally used in conjunction with a tank-type system. Its main problem has been its high cost. (4:32)

Ultrasonic cleaning has four critical components and processes for cleaning:

1. The generator, which produces electronic or rotary energy at resonant frequency of the transducer, generally converts line power to radio frequency power of desired frequency. (10:1) It can be an electronic oscillator with a 60-watt to many kilowatt output and is rated in average power or pulsated power (4 times average power). (18:52)

2. The transducer, which converts radio frequency power to mechanical energy at the same frequency, expands and contracts at the frequency of the generator. (10:1, 18:51) There are two types of transducers; the electrostrictive which expands and contracts in response to voltage alterations, and the magnetostrictive material which experiences a change in length when subject to a magnetic field. (17:51) Two common transducers are barium titanate, usually used at 40 kc/sec, and magnetostrictive materials, generally used at 20 kc/sec but do go up to 50 kc/sec. (18:51) The transducer is connected to the generator by co-axial conductor. (18:44) The frequency must be low enough to allow the bubbles to grow. (18:46)

3. A necessary process is the transmission of radio frequency power to the fluid.

4. Cavitation, which is the formation and collapse of microscopic bubbles, "literally blast(s) off the dirt." (18:45) As the bubbles form, the pressure is suddenly reduced in the area, releasing dirt and solid particles from the surface of the parts. The collapse of bubbles causes liquid pressures up to 100 atm. (2:25) Cavitation depends on surface tension, pressure, density, temperature, and viscosity. It is a stressed liquid (beyond tensile strength) that suddenly collapses on compression phase. (10:1) This creates a scrubbing action. Implosion is the collapse of bubbles during the pressure reduction. (18:51) The cavitation can produce transducer errosion. (17:47). The liquid only accepts a certain amount of power from a plain radiating surface; if the power becomes too high in the immediate vicinity of the radiating surface, one can get cavitation of the radiating surface. (17:54) Up to 20 watts per square inch may be used. The average power rather than peak power determines cleaning. (7:220) When the transducer is at one end of the tank, the other end must be at a node (odd-quarter wavelength) to produce a stable standing wave. (17:56)

A solvent or detergent is generally used along with water. (18:51) However, water is sometimes a better solution than detergent. (8:127). Some solutions will not support cavitation and must be degassed. Hot or cold solvents can be used but sonic action normally heats the solution. (18:52) The power required to produce cavitation increases as frequency increases with 20 to 100 kc/sec the best and 40 kc/sec generally chosen to provide high levels of cavitation at low-power levels. (18:54) The solution can be reclaimed by distillation or filtering. (18:56) A solution with a high-surface tension is desirable. (11:111) Mechanical agitation, such as shaking the parts basket, is desirable to remove dirt from parts. (8:127)

Small parts can be cleaned by putting them in a glass beaker which is immersed in the tank, (18:54) usually made of stainless steel. (17:54) Tank size is based on ratio of transducer capacity (installed watts) to solution volume. (8:126) Different sized parts and various soils require various frequencies; the frequency used is also dependent on where the soil is. (17:46-47) When baskets are used for parts, they should be greater than 1/4 inch mesh or less than 200 mesh. (17:60)

Other considerations not yet mentioned in design include transducer location (if more than one transducer is used, they should be located as close together for maximum effectiveness) (8:127) and part orientation.

English manufacturers of decorative flatware use ultrasonic. (11:111) See Ref. 3 from some applications including fragile glass.)

Ultrasonic energy cavitates aluminum foil due to cold working by pressure differentials. (4:33) This may present some problems with cleaning aluminum pans in an ultrasonic dishwasher.

Ultrasonic cleaning is safe, but one cannot put his hands in the tank for long periods of time since prolonged immersion results in burns. It does produce some noise but is not dangerous or objectional. (18:56)

F. SALT BATHS

Salt baths operate at high temperature, often with such salts as sodium hydride, Krolen No. 1, or Krolen No. 4. Due to the corrosive nature of salt and the difficulty in handling salt and cleaning dishes at high temperature, little information was collected on this subject. Reference 16 gives more information.

G. BRUSH SYSTEMS

A wide variety of things are cleaned by brush systems. Well-known examples are automatic car washes and the glass cleaners that are sometimes used to clean bar glasses. Apparently, due to technical simplicity of brush systems, no information is available. Obviously a brush system that would clean dishes would involve a complex system of brushes if it were to handle dishes of various shapes.

4. Evaluation of Basic Cleaning Methods

Each cleaning method discussed in the preceding section can certainly clean dishes, but each has different advantages. Practicality of use for a dishwasher is not being considered at this time.

In order to evaluate all the cleaning methods on an equivalent basis, a common basis for evaluating is given below. Present-day dishwasher may not hold up to the criteria listed, but this does not invalidate the criteria. Also, evaluating each method means predicting performance on the basis of what is presently known. Although predicting is always subject to error and criticism it was felt that this is the best that could be done on what is known from an extensive literature search. Criticism and disagreement are certainly in order.

A. Cleanliness - dishes must appear to be clean

1. no deposits of food
2. no greasy or oily films
3. no spotting of glassware

B. Sanitize - dishes must not contain any microorganisms (immediately after being cleaned) that are likely to cause infection. This requires no towel drying and may be accomplished in one of two ways:

1. Heat*
   a. 10-sec rinse at 170°F
   b. 2-min immersion at 170°F
   c. 1/2 min immersion at boiling temperature
2. Chemical - There are many chemicals available to sanitize dishes. The only important point is whether or not one of these can be used in conjunction with each cleaning method.

C. Materials that can be cleaned - Some materials suffer damage either by heat, chemical action, or mechanical scrubbing action. The materials considered are shown in Table I.

D. Dishes or color designs should not be damaged.

Table I contains an evaluation on a point basis of the above mentioned criteria. Ten points is the highest and means approximately 100% chance of success. Under sanitizing, the x's correspond to accomplishing sanitizing by the particular method indicated in the lefthand column. Each criterion is considered separately and it should be realized that any single dishwasher may not accomplish

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*This information was taken from an article titled "Sterilization of Dishes and Utensils in Eating Establishments"; however the article was discarded by the library before a complete bibliography was obtained. This information is also available in articles such as references 6:13 and 19:111.

TABLE I

METHOD EVALUATION

0 to 10 basis; 10 being most desirable
x means that the particular criteria may be accomplished in that manner

Criteria	Impact Cleaning	Solvent	Emulsion & Diphase	Vapor Degreasing	Ultra-sonic	Salt Bath	Brush System
A. Cleanliness							
1. No deposits of food	10	10	10	7	10	9	9
2. No greasy or oily films	10	10	5	10	10	10	10
3. No spotting of glassware	10	10	10	9	10	9	10
B. Sanitize							
1. Heat	10	10	10	10	10	10	10
a. 10-sec rinse at 170°F	x	x	x	x	x	x	x
b. 2-min immersion at 170°F	x	x	x	x	x	x	x
c. 1/2 min immersion at boiling		x		x	x	x	x
2. Chemical	x	x	x	x	x	x	x
C. Materials that can be cleaned							
1. Plastics	10	8	10	7	10	10	10
2. Aluminum	10	10	10	10	9	7	10
3. Copper	10	10	10	10	10	7	10
4. Glass	10	10	10	10	10	10	10
5. Pottery	10	10	10	10	10	10	10
6. China	10	10	10	10	10	10	10
7. Wood	10	10	10	10	10	10	10
8. Metal pots and frying pans	10	10	10	10	10	9	10
D. Dishes or color designs should not be damaged	9	10	7	10	10	10	10

all the criteria that are rated at 10. It is felt that each criterion rated at 10 could be accomplished but perhaps at the expense of other criteria that are also rated at 10.

A. DISCUSSION OF EVALUATION

The following discussion presents the author's reasons for assigning the values to the evaluation criterion as shown in Table I.

B. IMPACT CLEANING

As previously discussed, impact cleaning is used to clean a wide variety of materials, and impact cleaners can be made abrasive enough to clean a wide variety of hard-to-clean soils. On this basis, it is easy to imagine that impact cleaning can clean any type of soil found on dishes and a 10 was given for each cleanliness criterion.

An impact dishwasher could use water at any temperature, thereby sanitizing by heat under the first two criteria. The third criterion (immersion) would probably be unreasonable since a dip tank is not used in this process. Chemical sanitation would be simple since it would probably only involve adding one of many available sanitizing agents.

Many materials including glass, vitrolite, and china are cleaned by impact cleaning and hence it is felt that all materials listed in Table I can be handled and were rated 10. One obvious problem is achieving a balance between too much mechanical scrubbing action ruining the dishes and not enough mechanical scrubbing action to clean the dishes.

It is felt that water with particles in it will eventually lead to errosion of color designs on some dishes such as glasses. Therefore, 9 is assigned to "no damage being done to dishes or color design."

C. SOLVENT CLEANING

Solvents clean a wide variety of materials with a wide variety of soils to a high degree; hence, a rating of 10 is assigned to each cleanliness criterion.

Sanitizing, either by heat or chemical action, should not present any problem, and each criterion is assigned a value of 10.

As previously mentioned, plastics may suffer some damage from solvents. They are assigned a value of 8 while all other materials are assigned 10.

It is conceivable that a solvent could be used that would not damage dishes or color designs, so a value of 10 is assigned to that criterion.

D. EMULSION AND DIPHASE

As mentioned previously, emulsions tend to leave a thin oily film even after hot rinses. They receive only a 5 under "no greasy or oily films." The other problem with emulsions is that after some use and exposure to air they tend to turn to acid which in turn tends to ruin color designs. Therefore, "dishes or color designs should not be damaged" only received a value of 7.

E. VAPOR DEGREASING

Vapor degreasing is primarily for degreasing and may present some problems with food deposits and spotting of glassware; these are assigned values of 7 and 9, respectively.

Sanitizing either by heat or chemical action should not present any problem.

Vapor degreasing generally is high-temperature cleaning. This may present some problems with plastics which are assigned a rating of 7.

F. ULTRASONIC

Ultrasonic cleaning is a highly effective way to clean many materials. However, it may pit aluminum, which is assigned a value of 9. All other criteria received a value of 10.

G. SALT BATH

A salt bath dishwasher may present some problems with cleaning a wide variety of soils and spotting of glassware; hence "no deposit of food" and "no spotting of glassware" each are assigned values of 9.

Salt bath cleaning also presents some problems with materials that can be cleaned and these materials as shown in Table I received low values. The salt may hurt some materials but it is not known whether it will harm color designs or dishes in general, so a value of 10 was given to that criterion.

H. BRUSH SYSTEM

A brush system should be able to accomplish everything that is in the criteria column except that it may not be able to remove hard caked-on soils; hence, this criterion is assigned a value of 9 while all other criteria received 10.

5. Cleaning Methods and Their Adaptability for Use in a Dishwasher

Up to this point, the only concern for cleaning methods is whether or not they can clean dishes. This section discusses the possible problems and advantages of building a dishwasher using each type of cleaning method.

A. IMPACT CLEANING

Impact cleaning is very flexible. It can be accomplished with nozzle blast, mechanical blast, or tumbling. Many fluids can be used plus a wide variety of additives. As previously mentioned, impact cleaning is used to clean glass, vitrolite, and china. Due to the above-mentioned options and its present use to clean materials found in the kitchen, impact cleaning is certainly adaptable to cleaning and sanitizing dishes. Sanitizing could be accomplished either by heat or chemical action.

B. SOLVENT CLEANING

Solvent cleaning has found wide usage in assembly-line parts cleaning and dry cleaning; however solvents present a safety problem. It is still a basically reliable way to clean to a high degree and is adaptable to cleaning dishes.

C. EMULSION AND DIPHASE

Emulsion and diphase cleaning have not been given much attention because they leave a thin oily film. Emulsions also tend to turn to acid, which might run dishes. It is felt that because of these reasons, emulsion or diphase cleaning may not be adaptable to clean dishes.

D. VAPOR DEGREASING

Vapor degreasing is actually a solvent cleaning system where the solvent is in the vapor phase. It is generally done at elevated temperatures and may not be adaptable to cleaning dishes. Also solvent vapors generally present a safety and handling problem, making their adaptability to dishwashing difficult.

E. ULTRASONIC CLEANING

Ultrasonic cleans and sterilizes to a high enough degree to be used for sterilizing surgical instruments. It also cleans a wide variety of parts and materials. Obviously ultrasonic could be adapted to cleaning dishes.

F. BRUSH SYSTEM

Brush systems are relatively simple and an excellent way to clean many items. However, in order to clean dishes, a brush system would have to handle many different sizes, weights, and shapes, unless used for only a few types of dishes; hence a brush system would either be very limited in the dishes it could handle or it would be extremely complex. This would tend to make brush systems hard to adapt to cleaning dishes.

6. Feasibility of Building Dishwashers Using Various Cleaning Methods

This section discusses the feasibility of building various types of dishwashers in the laboratory using the cleaning methods discussed previously. Feasibility is taken to mean whether or not a dishwasher can be built that meets the criteria used to evaluate the cleaning methods.

A. IMPACT CLEANING

The many ways to build and operate an impact dishwasher make it particularly feasible to build in the laboratory. Laboratory work would mainly consist of building and testing a particular apparatus. It would also include investigation of possible damage or wear to dishes or color design.

B. SOLVENT CLEANING

Solvent cleaning can be accomplished with a hot or cold solvent using an immersion tank or spray system. Any system would be feasible and practical to build and laboratory work would include investigation of various solvents and the method in which to use and handle them. Laboratory work would also have to investigate whether or not all plastics could be cleaned with any particular system.

C. EMULSION AND DIPHASE

Emulsion and diphase cleaning can use three different types of cleaners in immersion bath or rinse systems. An emmulsifiable solvent is very effective in removing tightly adherent and heavy soils. However, laboratory work must be able to come up with a system that removes the thin oily film left by emulsion and diphase cleaners. Laboratory investigation would also have to investigate possible damage to plastics and color designs on dishes.

D. VAPOR DEGREASING

Vapor degreasing is another flexible process in that the solvent may be used in many or a combination of phases. This system is mainly used for degreasing metal parts, but a suitable solvent may be applicable for cleaning dishes; however, hard caked-on soils may not be removed and some plastics may be damaged by the solvent or temperature at which a given system is operated.

E. ULTRASONIC

Ultrasonic cleaning is very effective and is useful for a wide range of soils and materials. This process is presently in wide use for specialized cleaning where its high cost is justifiable. Many companies today are doing research and development to lower the price, which is its big fault. Laboratory work would be very feasible and would need to include a cost-reduction study.

F. SALT BATH

A salt bath could be a very effective cleaning process and would be very easy to build in the laboratory. Practical problems that must be overcome include an apparatus that would not be attacked by the salt, a salt that would not be harmful to dishes, and a rinse system that would remove salt and soil from the dishes.

G. BRUSH SYSTEM

Brush systems are easy to build and many chemical additives could be used to clean and sanitize the dishes. Laboratory work would include the development of a brush system or systems that could handle a reasonable variety of dishes and the investigation of various bristle compounds for expected lifetime.

7. Proposed Dishwashers

After reviewing all material up to this point, it was felt that three systems were the most promising; water impact, emulsion, and solvent. All three appeared to be equally good for cleaning dishes and reasonably adaptable. Sketches were made of possible ways to build each system (Figures 1, 3, and 4). A discussion of each system is included below.

A. WATER IMPACT SYSTEM

In the water impact system (Figure 1), the separator is necessary to keep the additive from getting into the drain and clogging it. If the pump that handles the abrasive cannot pump enough water, the nonabrasive pump could assist the abrasive pump by recirculating water to the nozzles. Other possible pump arrangements are shown in Figure 2.

B. SOLVENT

The solvent system chosen (Figure 3), incorporates an electric evaporator for solvent reclaiming. A preheater is used to reduce the electricity consumption for evaporation and a water condenser is used to condense the vapor.

C. EMULSION

A possible emulsion system is shown in Figure 4. As can be seen, the only change from the present dishwasher is the emulsion reservoir system. This system could also be used for a cold solvent that is not reclaimed and is pumped to the drain after each wash.

In cooperation with Whirlpool representatives, it was decided that within the span of time available, there was sufficient interest in the water impact system to warrant its being built and tested. To have desired flexibility with pump arrangements and the ease of mounting equipment on the testing apparatus, a casing was built (Figure 5), instead of rebuilding a conventional dishwasher. Presently the system is being worked on, and testing will be started when equipment problems are solved.

A similar system would involve a water rinse followed by an air-abrasive cleaning cycle. This system would be very similar to "sand blasting" and would have the advantage of being able to accomplish a higher velocity of the additive without the danger of dislodging dishes due to high fluid impact.

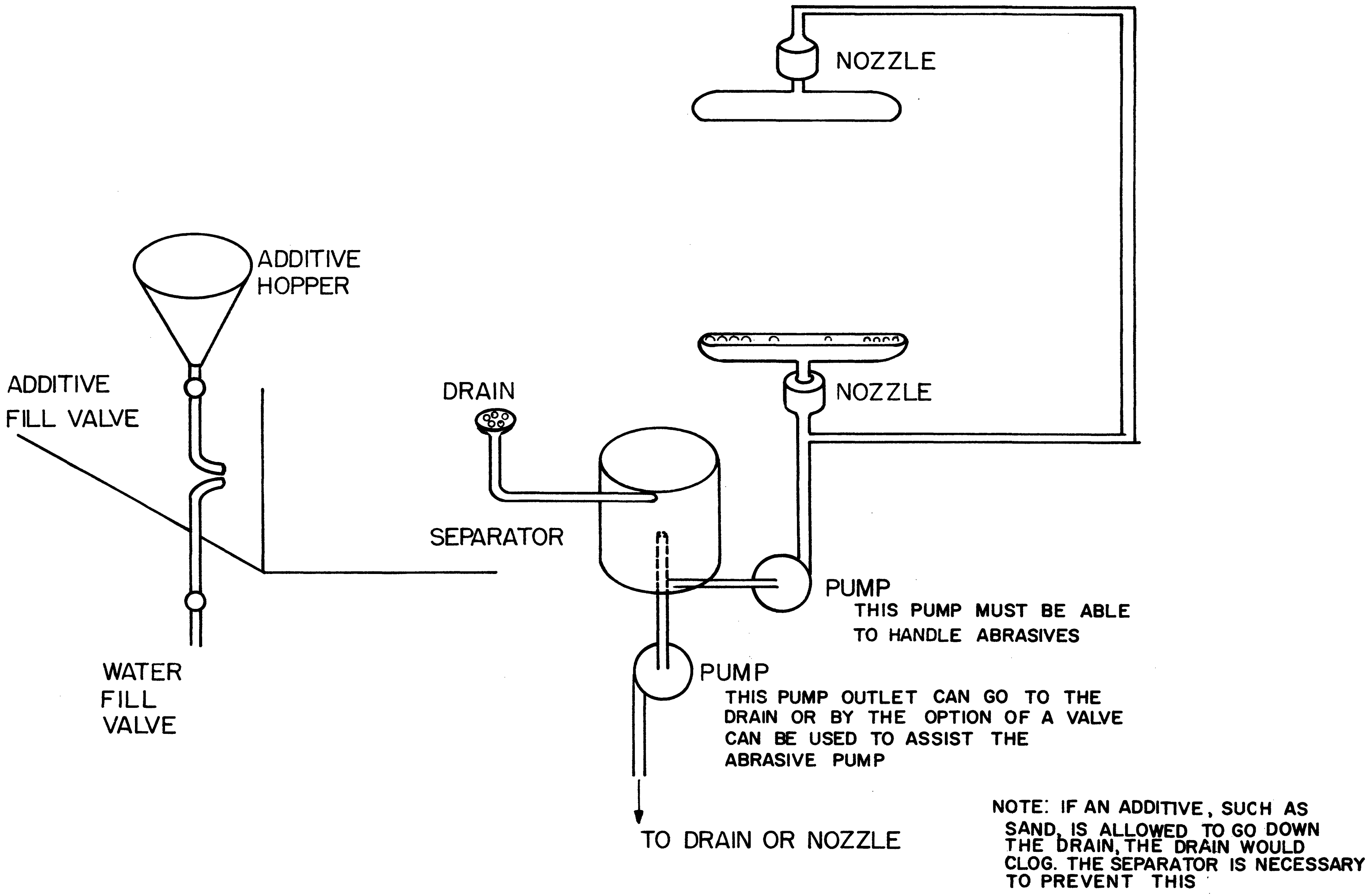

Fig. 1. Water impact system.

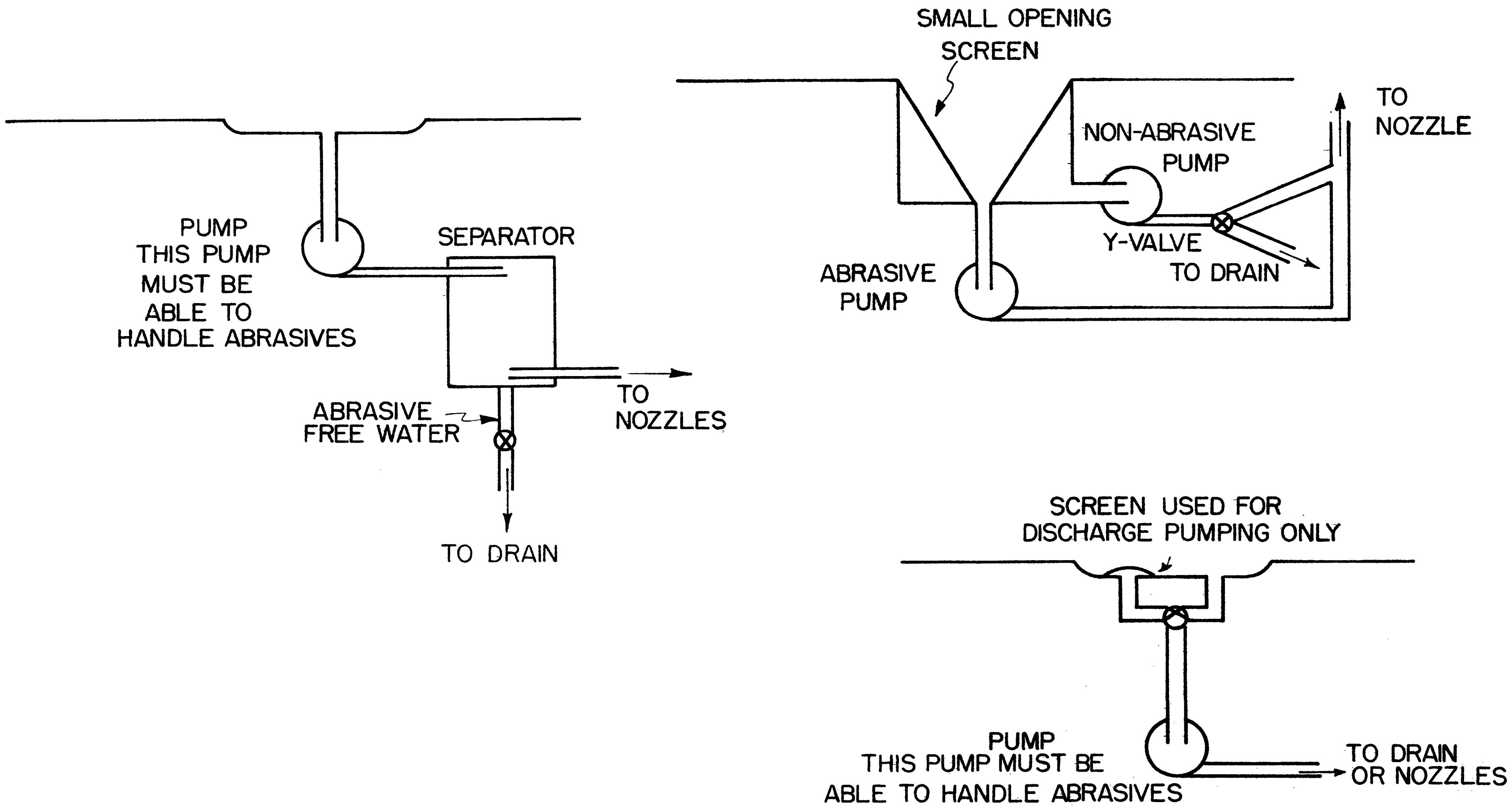

Fig. 2. Possible pump arrangements.

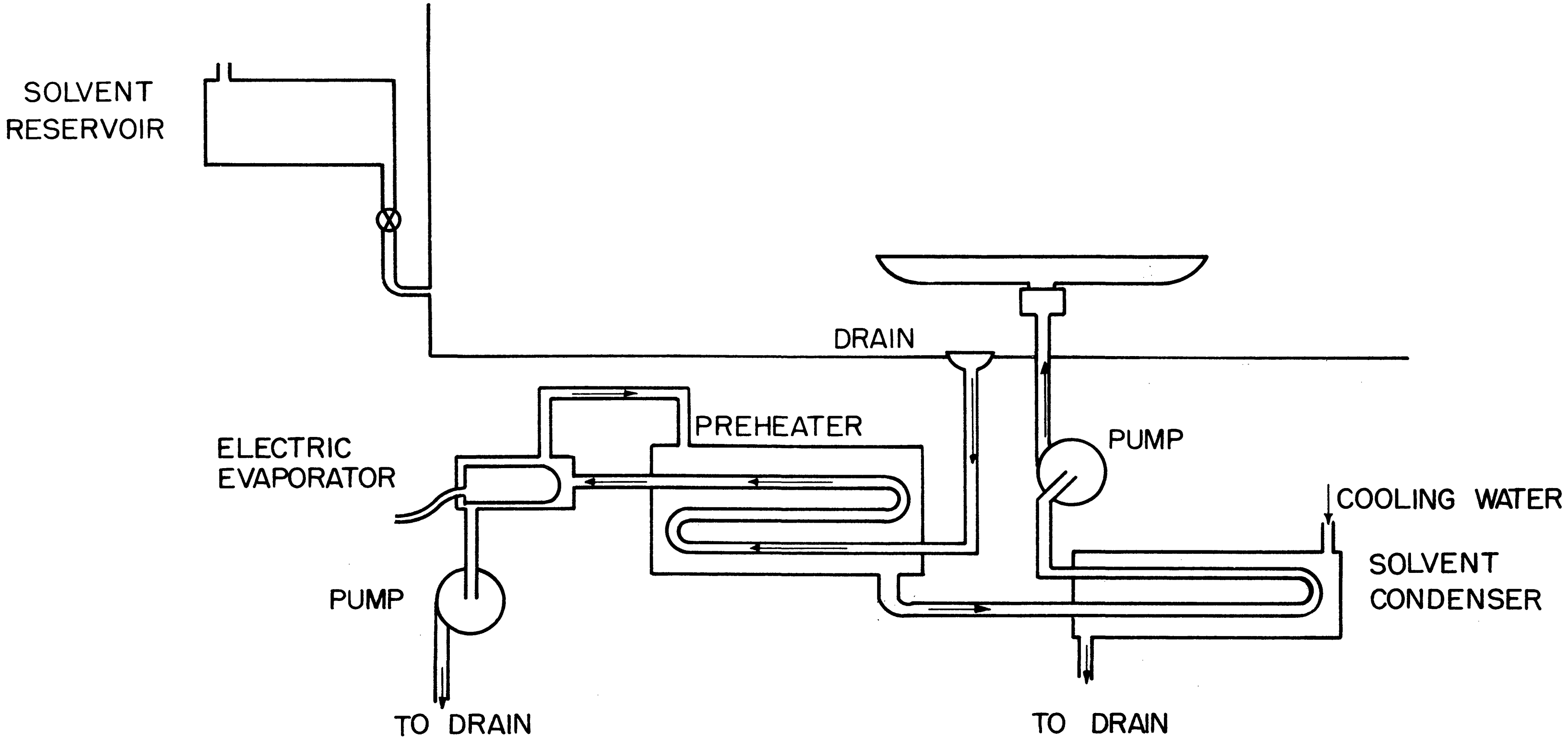

Fig. 3. Solvent (distillation reclaiming).

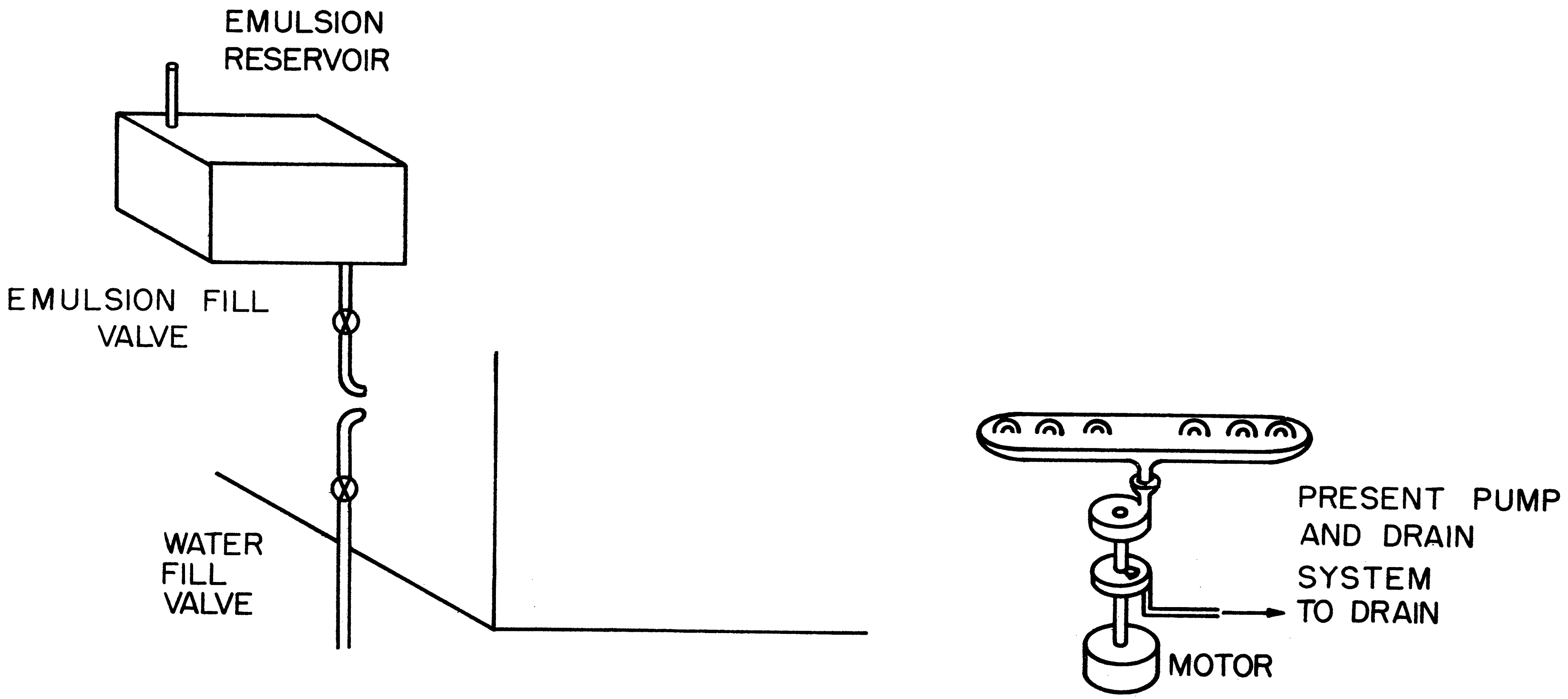

Fig. 4. Emulsion (can also be used for "cold" solvent that is not reclaimed).

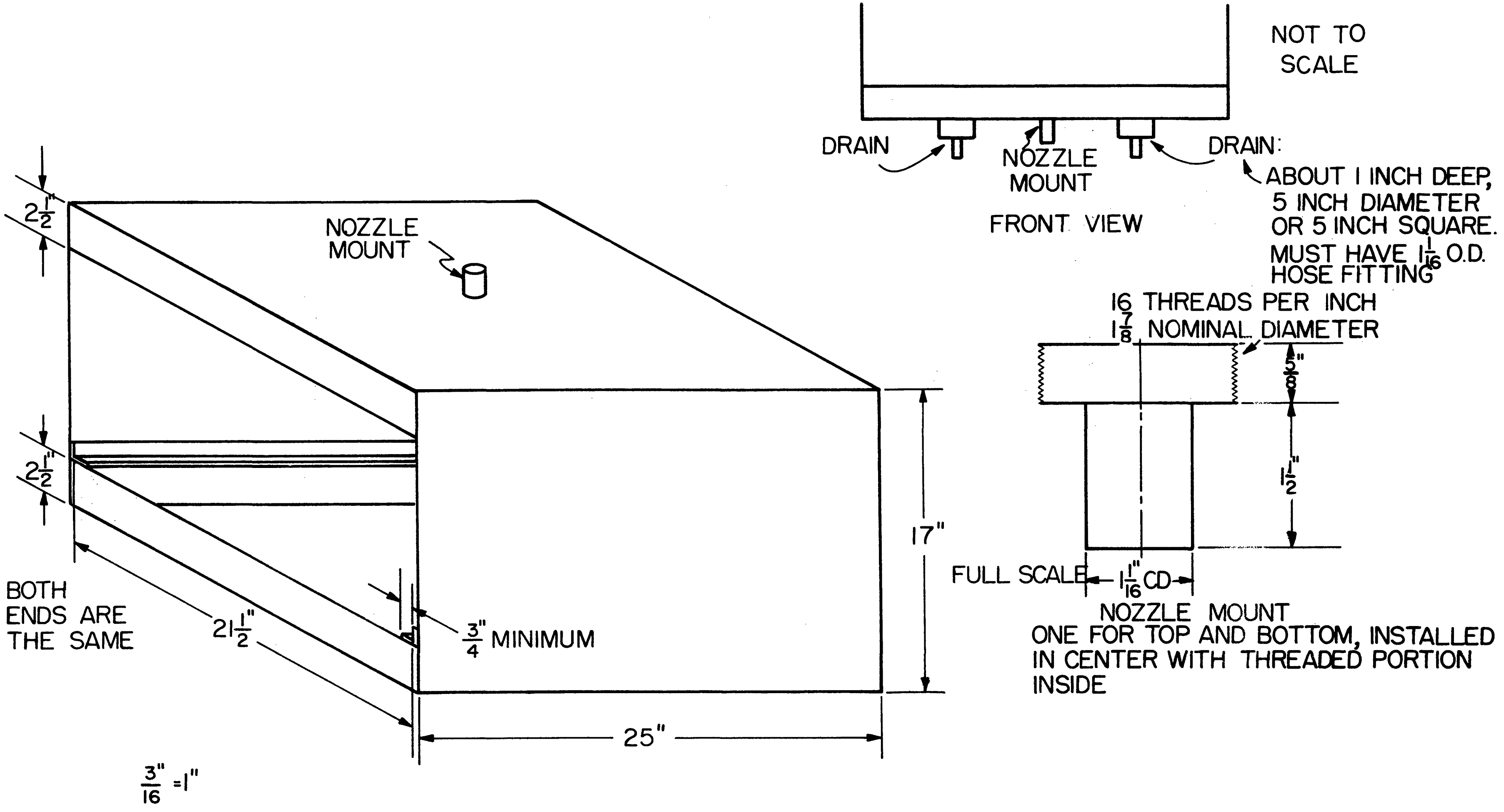

Fig. 5. Casing for water impact dishwasher.

8. Appendix

During the early stages of this project, much information was collected and is presently in this paper; however, many references that were educational, informative, and interesting to the author were not directly useful in writing this paper. These references that may be useful to the reader are presented in bibliographical form.

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WHIRLPOOL VACUUM EXTRACT COMBINATION WASHER/DRYER ANALYSIS OF THE VARIABLES IN THE EXTRACT AND DRYING CYCLES

Robert O. Rice

1. Introduction

This report is a description of a computer program that simulates the water extraction and drying process in the Whirlpool vacuum extract combination washer/dryer. The report includes the experimental data taken and the two computer programs written to simulate the process. Although the simululation is not at this time as accurate as would be needed for design use, this study has shown the feasibility of simulating this process in the combination washer/dryer. It is hoped that further work in this area will allow this type of simulation to aid the designer.

2. Conclusions

The moisture extraction process in the Whirlpool vacuum extract combination washer/dryer can be represented by two general categories. First, mechanical extraction which is characterized by a pressure drop across the cloth that causes the water to be removed in droplet form. Second, drying which is characterized by heat and mass transfer equations.

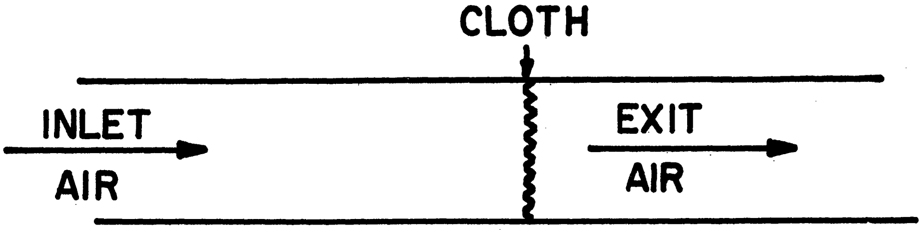
The heat and mass transfer coefficients, and the constants for mechanical extraction can be determined experimentally.

A computer program simulation of the process using experimentally determined constants can be written to simulate the moisture extraction in the Whirlpool vacuum combination washer/dryer.

3. Results

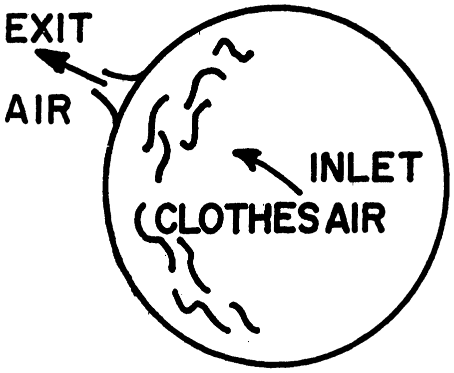
Two computer programs have been written to simulate the water extraction and drying process in the vacuum extract combination washer/dryer.

The first program simulates a single piece of cloth during water extraction and drying.



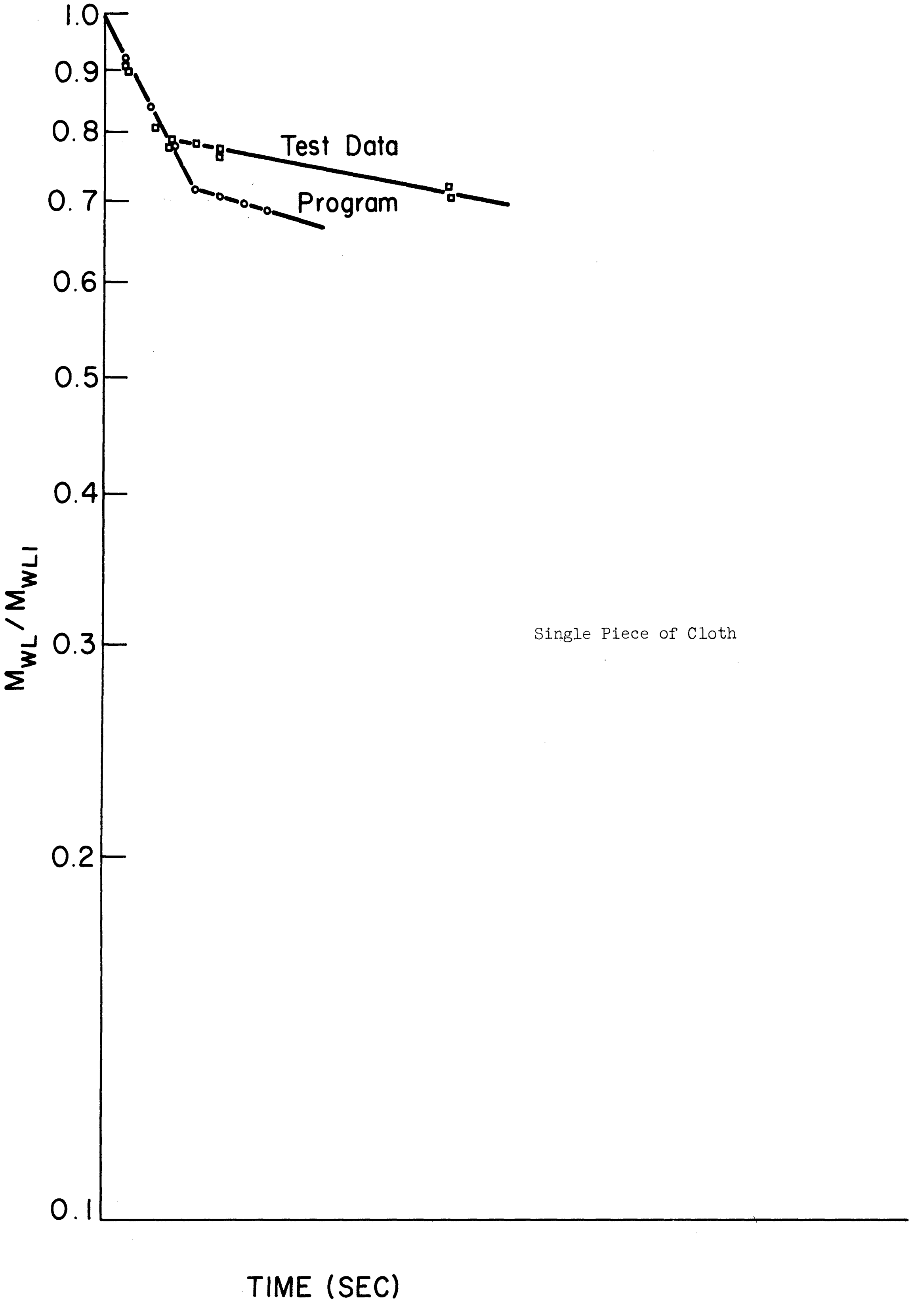
The comparison of the test results with the computer program simulation is shown on page 48. The difference in the two results is due to a programming error which allows the extraction process to continue too long. This error can be corrected as shown in the program listing in Appendix B.

The second computer program simulates the water extraction and drying process for the vacuum extract washer/dryer machine.

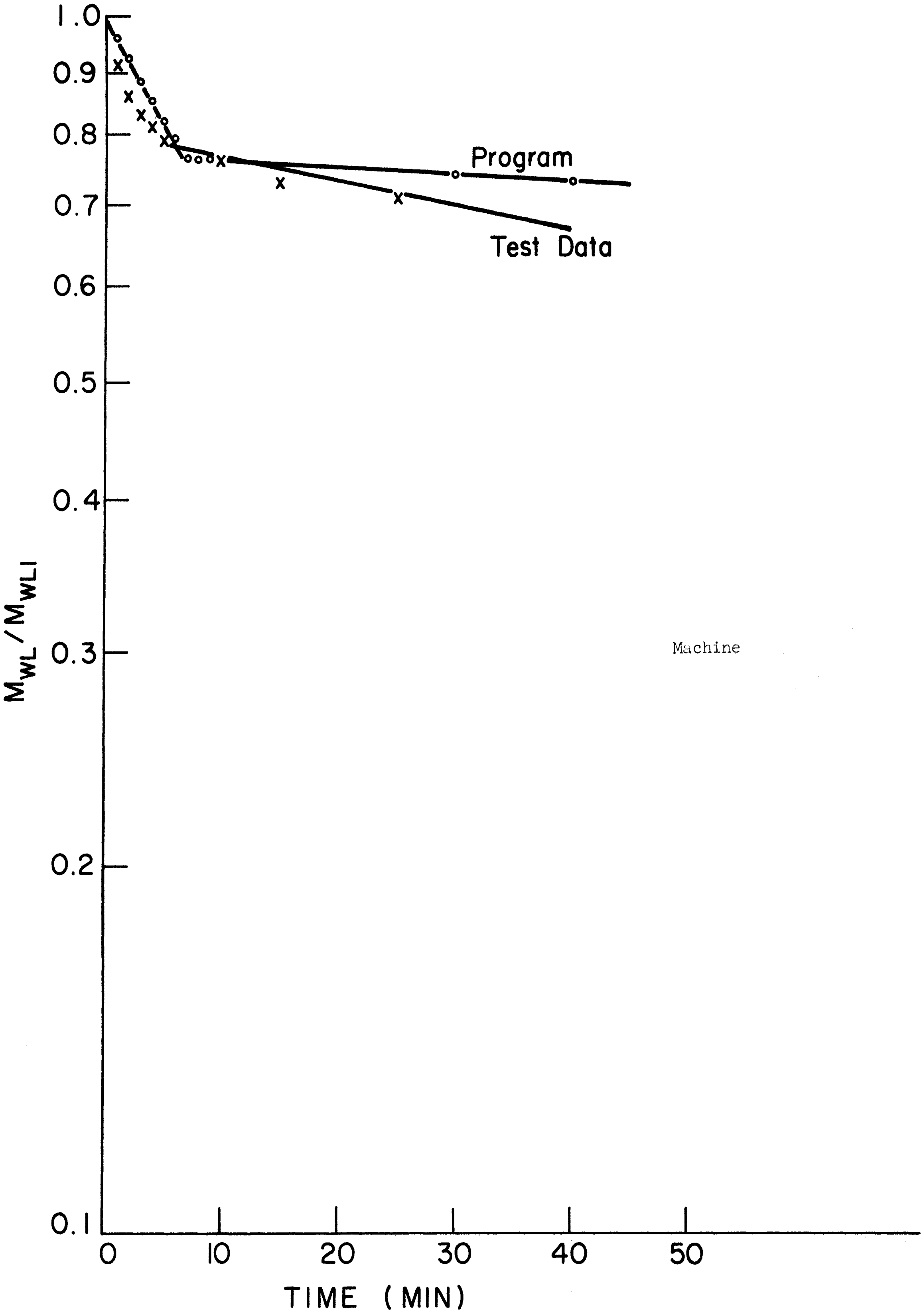


The comparison of the test results with the computer simulation is shown on page 49. The results of the drying portion do not fit the test data very well because further experimental data is needed on the factors involved in the tumbling process.

The accuracy of the program in fitting the experimental data is a function of the limits set on the factors ROR and JKR (see p. 59). These two factors should equal zero, but because of the computer they are set arbitrarily small. The smaller they are set, the more iterations the computer must make and the longer the program takes to run. The length of execution time has been the biggest limitation of the program. It is possible that this limitation can be eliminated by specifying a range of inlet temperatures, thereby reducing the number of iterations the program must make.



Single Piece of Cloth



1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
M_{WL}/M_{WLI}
0
10
20
30
40
50
TIME (MIN)
Program
Test Data

Machine

4. Result Uncertainty

In the mechanical extraction experimental results, the following possible errors were recognized:

(a) The data did not conform exactly to the straightline drawn for this portion of the curve. Some of this difference can be attributed to the drying that was occurring at the same time, while any other must be attributed to the inaccuracy of measurement of the initial mass of water. This measurement was difficult because water is easily lost in the move from the weighing scale to the system before the pressure drop across the cloth was created.

(b) In measuring the pressure drop across the orifice and the cloth, the inertia forces in the manometer could have introduced error due to the rapid change that had to be measured.

In the drying portion of the mechanical extraction, the following possible errors were recognized:

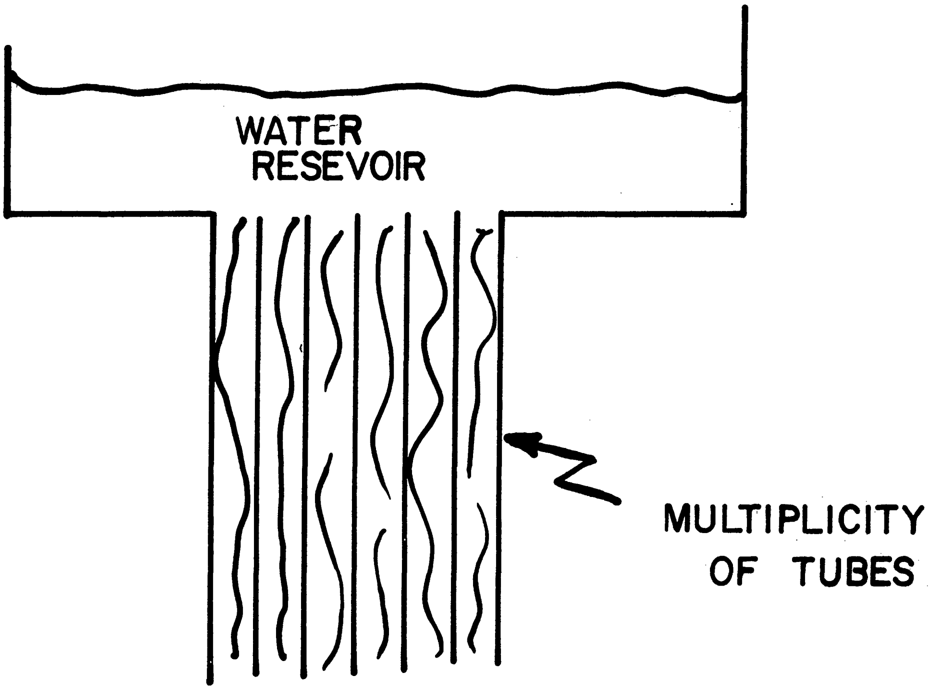
(a) As discussed in the experimental procedure section, it was difficult to obtain an accurate measuring system for the wet bulb temperatures. The instrument used to check the validity of these results was the sling psychrometer.

(b) The recording instrument used for the wet and dry bulb temperature was a potentiometer. The millivolt readings were recorded on paper rolls by the instrument, then converted to temperatures by use of a millivolt-temperature conversion table. Although the introduction of large error seemed possible in this conversion, the computer program and data comparison seem to indicate that this did not occur.

5. Mechanisms of Moisture Extraction

The process of water extraction can be broken down into two main mechanisms. The first is mechanical extraction, and the second is by vaporization.

In mechanical extraction, water droplets are removed from the cloth by body and surface forces. The body forces are due to gravity, and the surface forces are created by placing a pressure drop across the cloth. The following model was used to represent this process.

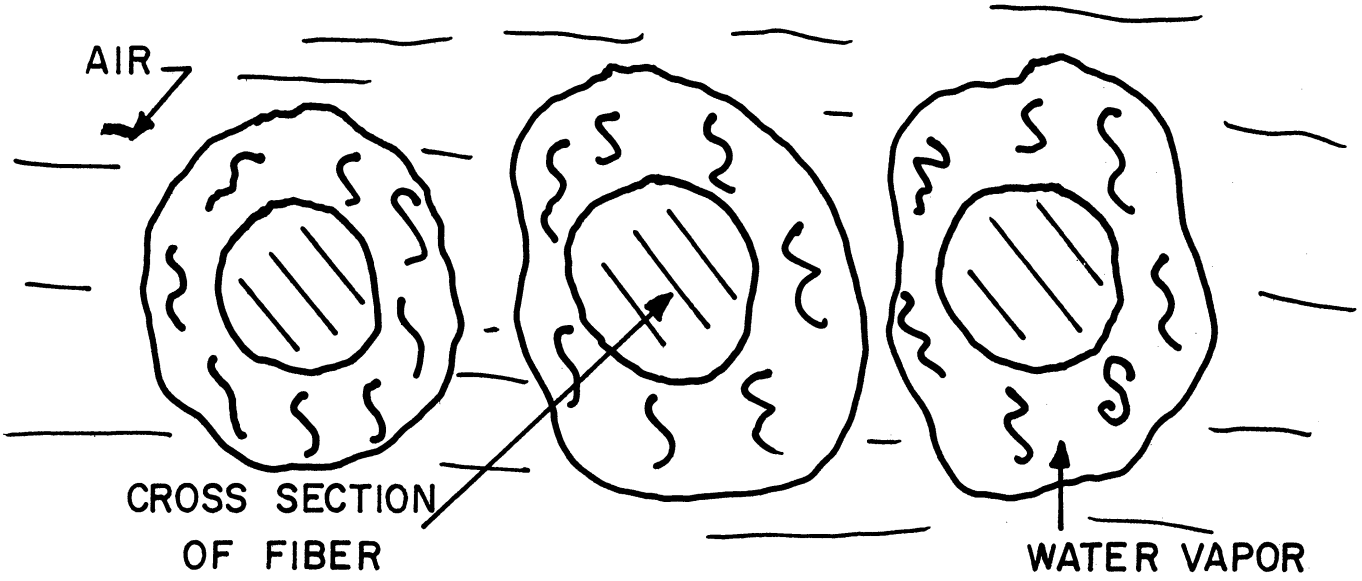


Continuity Equation

$$\frac{dm}{dt} = -\rho AV = -\frac{\rho A\Delta P}{C} = K\Delta P$$

dm/dt = mass rate of change of water liquid
ρ = density of the water
A = area of the tubes
ΔP = pressure drop across the cloth
C = constant
K = constant

The moisture extraction by vaporiation can be represented by Fick's Law for diffusion.



Fick's Law

$$\text{Rate} = - D \frac{\partial C}{\partial S}$$

D = diffusion coefficient
$\partial C/\partial S$ = concentration gradient

This equation is analogous to the heat transfer equation (Rate $= - K \frac{\partial T}{\partial X}$), but in the case of diffusion, the effective film thickness cannot be measured directly, so the equation is rewritten analogous to the heat transfer equation as:

$$\text{Rate} = \text{Hmtx}\ (\text{Psat} - \text{Pvap})$$

Hmtx = mass transfer coefficient
Psat = saturation press of the water liquid
Pvap = vapor pressure of the water vapor in the air

6. Single Piece of Cloth Computer Program

A computer program has been written to simulate the water extraction and drying process to determine what effect variable changes in the process will have.

A. MECHANICAL EXTRACTION

This is the process by which water is extracted from the cloth mechanically by creating a pressure drop across the cloth with a blower. The following equations, representing this process, were determined experimentally (p. 64).

1. $M_{WL2} = M_{WL1}\, e^{-.0065 P_{C1}}$, for M_{WL}/M_{WLI} $c = e^{-.0222 P_{CII}}$

M_{WL1} = mass of water liquid in the cloth at time T_1

M_{WL2} = mass of water liquid in the cloth at time T_2

M_{WLI} = initial mass of water in the cloth

P_{CI} = initial pressure drop across the cloth

Program Notation

C = 2.71828.P.(-.0222*PCI)

```
X2 = .0065*PCI

WHENEVER MWL/MWLI .G. C

  MWL - MWL*(2.71828.P.(-X2))
```

2. $P_C = P_{CI}(M_{WL}/M_{WLI})$

P_C = pressure drop across the cloth at time T

P_{CI}= initial pressure drop across the cloth

Program Notation

```
PC = PCI*MWL/MWLI
```

3. $V_{AI} = V_{AIF}\sqrt{1.35 - P_C/P_{CI}}$

V_{AI} = velocity of the air entering at time T

V_{AIF}= maximum velocity of the air entering

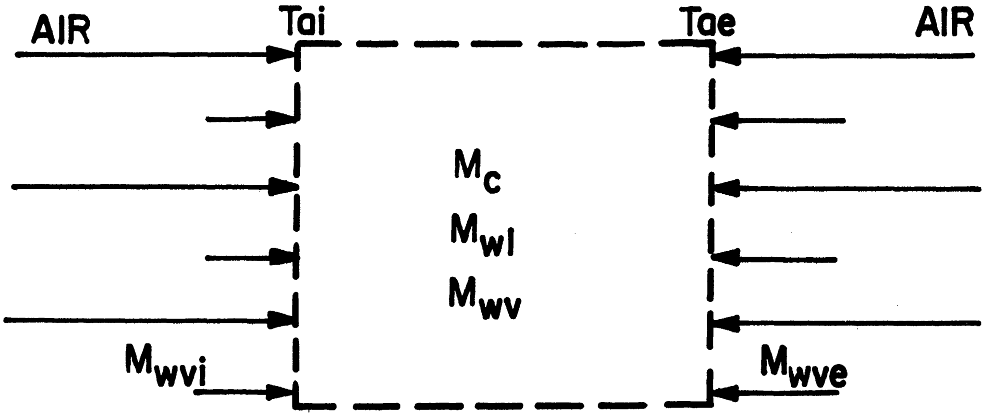
Program Notation

V_{AI} = VAIF*(1.35 - PC/PCI).P. .5

B. DRYING

This is the process by which water is extracted from the cloth by the vapor pressure gradient between the cloth and the air.

The system for the drying process was considered as shown below:



T_{AI} = temperature of the air at the inlet

T_{AE} = temperature of the air at the exit

M_{WVI} = mass of water vapor at the inlet

M_{WVE} = mass of water vapor at the exit

M_C = mass of the cloth

M_{WL} = mass of liquid water in the cloth

M_{WV} = mass of water vapor in the cloth

The following four assumptions were made about the system.

1. The temperature of the water vapor at the inlet and exit equals the temperature of the air at the inlet and exit, respectively.

2. The mass of the cloth, water liquid, and water vapor in the cloth are all at the same temperature.

3. The temperatures involved in the heat transfer to the cloth are the temperature of the cloth (T_C) and the average of the inlet and exit temperatures (T_{AVE}).

4. The change in mass of the water vapor in the cloth during the process is equal to zero ($\dot{M}_{WVC} = 0$).

The basic equations used to define the process are:

Continuity Equation:

1. $\dot{M}_{AI} = \dot{M}_{AE}$

   $\dot{M}_{AI}$ = mass flow rate of air at the inlet

   $\dot{M}_{AE}$ = mass flow rate of air at the exit

2. $\dot{M}_{WVC} = \dot{M}_{WL} - \dot{M}_{WVT} = 0$

   $\dot{M}_{WVC}$ = change in the mass of water vapor in the cloth

   $\dot{M}_{WL}$ = change in the mass of water liquid in the cloth

   $\dot{M}_{WVT}$ = change in the mass of water vapor transported from the cloth to the air

Energy Equation:

3. $\dot{Q} + \dot{M}_{AI}H_{AI} + \dot{M}_{WVI}H_{WVI} = \dot{U} + \dot{M}_{AE}H_{AE} + \dot{M}_{WVE}H_{WVE}$

$\dot{Q}$ = heat transfer rate from the system

$\dot{U}$ = change in internal energy of the cloth, water liquid, and water vapor in the cloth.

H = enthalpy of the mass per pound mass

Program Notation

ROR = MDAI*HAI + MWVI*HWVI - (UD + MDAE*HAE + MDWVE*HWVE)

Heat Transfer Equation:

4. $\dot{Q}_{AC} = A_{CL}H_{HTX}(T_{AVE}-T_C)\dot{M}_{AI}$

$\dot{Q}_{AC}$ = heat transfer rate from the air to the cloth

A_{CL} = area of the cloth

H_{HTX} = heat transfer coefficient of the cloth

Program Notation

QDAC = ACL*HHTX*(TAVE-TC)*MDAI

Mass Transfer Equation:

5. $\dot{M}_{WL} = A_{CL}H_{MTX}(P_S-P_V)\dot{M}_{AI}(144)$

$\dot{M}_{WL} = \dot{M}_{WVT}$ = mass of water vapor transported from the cloth to the air

H_{MTX} = mass transfer coefficient of the cloth

P_S = saturation pressure of the water vapor at the temperature of the cloth

P_V = vapor pressure of the water vapor in the entering air

Program Notation

MDWL = ACL*HMTX*(PS-PV)*MDAI*144

Equations Derived from Assumptions:

6. $\dot{U} = \dot{Q}_{AC} - \dot{M}_{WL}(H_V - H_F)$, from assumption 4 ($\dot{M}_{WVC}=0$)

H_V = enthalpy of the water vapor per pound mass

H_F = enthalpy of the water liquid per pound mass

Program Notation

```
UD = QDAC - MDWL*(HVTC-HLTC)
```

7. $\dot{U} = C_C M_C T_C + H_F \dot{M}_{WL} + \dot{H}_F M_{WL}$, from assumptions 1, 2, and 4

C_C = specific heat of the cloth

$\dot{U}$ = changes in internal energy of the mass of liquid water in the cloth per pound mass

Program Notation

```
JKR = UD - (CC*MC*TDC-MDWL*HWLTC+HDWLTC*MWL)
```

C. FALLING RATE PERIOD

In this period the drying rate decreases because the mass of water that diffuses to the surface of the fibers is less than the mass of water that could be removed by the vapor pressure gradient between the water in the cloth and the air.

The following equations for this period are taken from the Chemical Engineers Handbook (pp. 15-39).

7. $\dot{M}_{FR} = \dot{M}_{WL}(W - W_E)/W_C - W_E)$

$\dot{M}_{FR}$ = mass rate of water removed in the falling rate period

W = mass of water in the cloth/mass of the cloth

W_C = critical mass of water in the cloth/mass of the cloth

W_E = mass of water in the cloth in equilibrium with the mass of water in the air/mass of the cloth

Program Notation

```
W = MWL/MC

WHENEVER W .LE. WC,MDWL = MDWL(W-WE)/(WC-WE)
```

D. GENERAL PROCEDURE

The following procedure is used for the program. At a given time T, the mass of water removed due to mechanical extraction is determined. Next temperatures, pressures, and mass necessary to calculate the heat and mass transfer rates, and the rate of change of internal energy in the cloth are found. These values are held constant over the time internal and the mechanical extraction water removal, temperatures, pressures, and masses at time T+1 are calculated. This procedure is repeated until the mass of water liquid in the cloth is in equilibrium with the air.

E. SPECIFIC PROCEDURE

1. Data Input

The following data must all be entered as input, but may be entered in any order.

TAI - temperature of the inlet air (°F)
VAIF - volume flow rate of air when the cloth is dry (cu ft/min)
ACL - area of the cloth
MWVI - mass of water vapor entering (lb water vapor/lb dry air)
MWLI - initial mass of water in the cloth
TOTPA - total pressure of the inlet air and water vapor
PCI - initial pressure drop across the cloth (in. of water)
MC - mass of the cloth (lb)
CC - specific heat of the cloth
TC - initial temperature of the cloth (°F)
WC - critical moisture content of the cloth (mass water/mass cloth)
WE - equilibrium content of water in the cloth with the air (mass water/mass cloth)
PTIME - the interval in seconds between the printing of output (this must be an integer)

1. Example - two cards

```
/TAI=76.,VAIF=90.,ACL=.196,MWVI=.0036,MC=.02,MWLI=.07,TC=65.,

/CC=.3,PCI=12.,TOTPA=14.7,WC=.25,WE=.01,PTIME=1        *
```

2. Sample Calculations of Program Operations Using Example Data

The program first calculates the constants used later in the iterations.

C = 2.71828.P.(-.0222*PCI) = .775

X2 = .0065*PCI = .078

PV = MWVI*TOTPA/(.622 + MWVI) = .0845

Then the iterations of time are started by setting time = 1.

With time = 1, the water extracted by mechanical extraction, the pressure across the cloth, and the volume flow rate of air entering are calculated.

MWL = MWL*(2.71828.P.(-X2)) = .0648

PC = PCI*MWL/MWL1 = 11.1

VAI = VAIF*(1.35 - PC/PCI).P. .5 = 58.6

Next the program begins the calculations to find the exit temperature of the air. This is an iterative process and only one iteration will be shown. The first step is to assume a value of the exit temperature and make all calculations using the assumed value.

TL = TC = 65

TR = TAI = 76

TAE = .5*(TR + TL) = 0.75

TAVE = .5*(TAI + TAE) = 73.25

PS = PSATT.(TC) = .3056 From steam tables external function

ARHO = 2.698*TOTPA/(TAVE + 460) = .0746

MDAI = VAI*ARHO/60 = .073

QDAC = ACL*HHTX*(TAVE - TC)MDAI = .218

MCWL = ACL*HMTX*(PS - PV)*144*MDAI = .00601

HLTC = HFT.(TC) = 33.05

From steam tables external function

HVTC = HGT.(TC) = 1090.2

UD = QDAC - MDWL*(HVTC - HLTC) = -6.13

HAI = 119.5 + .24*(TAI - 40) = 128.1

HAE = 119.5 + .24*(TAE - 40) = 126.8

MDWVI = MWVI*MDAI = .000263

MDAE = MDAI = .073

MDWVE = MDWVI + MDWL = .00627

MWVI = HGT.(TAI) = 1094.9

HWVE = HGT.(TAE) = 1092.4

These results are now used to check for a balance in the energy equation.

ROR = MDAI*HAI + MDWVI*HWVI-(UD + MDAE*HAE + MDWVE*HWVE) = 3.32

Since the energy equation does not balance, the program sets TL = TAE and goes through the process until ROR is less than .1. If ROR had been less than zero, the program would have set TR = TAE and repeated the process.

When ROR has been found to equal zero, the change in the temperature of the cloth is found. The procedure is generally the same as to find the exit temperature.

Given that the exit temperature was found to be 72.5,

TLI = 35

TRI = TAI = 76

TDC = .5*(TRI + TLI) - TC = -9.5

TCTDC = TC + TDC = 55.5

Hwltc = HFT.(TC) = 33.05

MDWLTC = HFT.(TCTDC) - HFT.(TC) = -9.48

JKR = (UD-(CC*MC*TDC-MDWL*HWLTC + HDWLTC*MWL) = -4.6

With this not zero, the program would go though the same type of iteration process that it did in the previous section.

3. Results Format

The results are printed out in a format as follows:

TIME, sec	MWL, lb	PC, lb/in.^{2}	-VAI, ft^3/min	TC, °F	TAE, °F	TAVE, °F

RESULTS—SINGLE PIECE OF CLOTH COMPUTER PROGRAM

```
 TIME     MWL      PC        VAI        TC        TAE       TAVE
    1   .0641  11.0996   58.6753   58.0625   67.7500   71.8750
    2   .0589  10.1715   63.7906   55.5000   62.5469   69.2734
    3   .0540   9.3355   68.0701   55.5000   60.6250   68.3125
    4   .0495   8.5679   71.7753   55.5000   60.6250   68.3125
    5   .0491   8.4913   72.1344   55.5000   60.6250   68.3125
    6   .0486   8.4144   72.4934   55.5000   60.6250   68.3125
    7   .0482   8.3371   72.8525   55.5000   60.6250   68.3125
    8   .0477   8.2594   73.2116   55.5000   60.6250   68.3125
    9   .0473   8.1813   73.5706   55.5000   60.6250   68.3125
   10   .0468   8.1028   73.9297   55.5000   60.6250   68.3125
   11   .0463   8.0240   74.2888   55.5000   60.6250   68.3125
   12   .0459   7.9447   74.6478   55.5000   60.6250   68.3125
   13   .0454   7.8651   75.0069   55.5000   60.6250   68.3125
   14   .0449   7.7851   75.3660   55.5000   60.6250   68.3125
   15   .0445   7.7048   75.7251   55.5000   60.6250   68.3125
   16   .0440   7.6240   76.0842   55.5000   60.6250   68.3125
   17   .0435   7.5428   76.4433   55.5000   60.6250   68.3125
   18   .0430   7.4613   76.8024   55.5000   60.6250   68.3125
   19   .0426   7.3794   77.1615   55.5000   60.6250   68.3125
   20   .0421   7.2971   77.5206   55.5000   60.6250   68.3125
   21   .0416   7.2144   77.8798   55.5000   60.6250   68.3125
   22   .0411   7.1314   78.2389   55.5000   60.6250   68.3125
   23   .0406   7.0479   78.5980   55.5000   60.6250   68.3125
   24   .0401   6.9641   78.9571   55.5000   60.6250   68.3125
   25   .0396   6.8799   79.3163   55.5000   60.6250   68.3125
   26   .0391   6.7953   79.6754   55.5000   60.6250   68.3125
   27   .0386   6.7103   80.0345   55.5000   60.6250   68.3125
   28   .0381   6.6250   80.3937   55.5000   60.6250   68.3125
   29   .0376   6.5392   80.7528   55.5000   60.6250   68.3125
   30   .0371   6.4531   81.1120   55.5000   60.6250   68.3125
   31   .0366   6.3666   81.4711   55.5000   60.6250   68.3125
   32   .0361   6.2797   81.8303   55.5000   60.6250   68.3125
   33   .0356   6.1924   82.1894   55.5000   60.6250   68.3125
   34   .0351   6.1048   82.5486   55.5000   60.6250   68.3125
   35   .0346   6.0167   82.9078   55.5000   60.6250   68.3125
   36   .0341   5.9283   83.2669   55.5000   60.6250   68.3125
   37   .0335   5.8395   83.6261   55.5000   60.6250   68.3125
   38   .0330   5.7503   83.9853   55.5000   60.6250   68.3125
   39   .0325   5.6608   84.3445   55.5000   60.6250   68.3125
   40   .0320   5.5708   84.7037   55.5000   60.6250   68.3125
```

7. Machine Computer Program

A computer program has been written but not completed for the vacuum extract combination washer/dryer. The factors still needed for the completion of this program are the average time the cloth covers the nozzle and the average thickness of the cloth covering the nozzle. The program as of this time has the same procedure as the single cloth program except for the changes discussed below.

A. MECHANICAL EXTRACTION

1. $M_{WLN} = M_{WL}M_{CN}/M_C(60)K$

M_{WLN} = mass of water liquid at the nozzle

M_{WL} = total mass of water liquid in the clothes

M_{CN} = mass of cloth at the nozzle

M_C = total mass of the clothes

K = percentage of the time the clothes cover the nozzle

Program Notation

```
MWLN = MWL*MCN/MC*60*K
```

2. $M_{WLN2} = M_{WLN1}\,e^{-.0065PCI(60)K}$, for M_{WL}/M_{WlI} $C = e^{-.0222PCI}$

Program Notation

```
C  = 2.71828.P.(-.0222*PCI)

X2 = .39*PCI*K

WHENEVER MWL/MWLI .G. C

  MDWLN = MWLN(1-2.71828.P.(-X2))

  MWL = MWL - MDWL
```

B. DRYING

1. $\dot{Q}_{AC} = A_{CL}H_{HTX}(T_{AVE} - T_C)\dot{M}_{AI}KI(K)$

   KI = number of thicknesses of one piece of cloth covering the nozzle on the average

   Program Notation

```
QDAC = ACL*HHTX*(TAVE - TC)*MDAI*KI*K
```

2. $\dot{M}_{WLN} = A_{CL}H_{MTX}(P_S - P_V)144M \quad KI(K)$

   Program Notation

```
MDWLN = ACL*HHTX*(PS - PV)*144*MDAI*KI*K
```

3. Output Format

TIME,	MWL,	PC,	VAI,	TC,	TAE,	TAVE,
sec	lb	lb/in.^{2}	ft^3/min	°F	°F	°F

RESULTS—MACHINE COMPUTER PROGRAM

```
TIME    MWL       PC        VAI       TC        TAE       TAVE
   1 14.8023 11.5427 62.2981 64.5889 71.5313 73.7656
   2 14.2270 11.0947 65.2258 64.1685 71.3642 73.6821
   3 13.6735 10.6636 67.9243 63.7480 71.1934 73.5967
   4 13.1408 10.2486 70.4234 63.3276 71.0226 73.5113
   5 12.6283  9.8494 72.7472 62.9072 70.9509 73.4754
   6 12.1353  9.4653 74.9150 62.4868 70.7833 73.3917
   7 11.6609  9.0957 76.9430 62.0864 70.6158 73.3079
   8 11.6493  9.0865 76.9932 61.7061 70.4563 73.2282
   9 11.6378  9.0773 77.0425 61.3657 70.3048 73.1524
  10 11.6265  9.0684 77.0908 61.0554 70.1692 73.0846
  11 11.6154  9.0596 77.1383 60.7651 70.1623 73.0811
  12 11.6044  9.0510 77.1851 60.5049 70.0489 73.0244
  13 11.5936  9.0424 77.2311 60.2646 69.9472 72.9736
  14 11.5830  9.0340 77.2765 60.0444 69.8534 72.9267
  15 11.5724  9.0257 77.3214 59.8442 69.7674 72.8837
  16 11.5619  9.0174 77.3658 59.6641 69.6892 72.8446
  17 11.5516  9.0093 77.4096 59.5039 69.6188 72.8094
  18 11.5413  9.0012 77.4531 59.3438 69.5562 72.7781
  19 11.5311  8.9932 77.4962 59.2036 69.4937 72.7468
  20 11.5210  8.9853 77.5389 59.0835 69.4389 72.7195
  21 11.5109  8.9774 77.5813 58.9634 69.3920 72.6960
  22 11.5009  8.9695 77.6235 58.8633 69.3451 72.6725
  23 11.4909  8.9617 77.6653 58.7632 69.3060 72.6530
  24 11.4810  8.9540 77.7070 58.6731 69.2669 72.6334
  25 11.4711  8.9462 77.7484 58.5830 69.2317 72.6158
  26 11.4613  8.9385 77.7896 58.5029 69.1965 72.5982
  27 11.4515  8.9309 77.8306 58.4329 69.1652 72.5826
  28 11.4417  8.9232 77.8714 58.3628 69.1378 72.5689
  29 11.4320  8.9156 77.9121 58.3027 69.1105 72.5552
  30 11.4223  8.9081 77.9526 58.2427 69.0870 72.5435
  31 11.4126  8.9005 77.9930 58.2026 69.0635 72.5318
  32 11.4030  8.8930 78.0333 58.1626 69.0479 72.5240
  33 11.3934  8.8854 78.0734 58.1226 69.0323 72.5161
  34 11.3837  8.8779 78.1135 58.0825 69.0166 72.5083
  35 11.3741  8.8704 78.1535 58.0425 69.0010 72.5005
  36 11.3645  8.8629 78.1934 58.0125 68.9853 72.4927
  37 11.3549  8.8555 78.2332 57.9824 68.9736 72.4868
  38 11.3454  8.8480 78.2730 57.9624 68.9619 72.4809
  39 11.3358  8.8406 78.3127 57.9424 68.9541 72.4770
  40 11.3263  8.8331 78.3523 57.9224 68.9462 72.4731
```

8. EXPERIMENTAL PROCEDURES

A. MECHANICAL EXTRACTION

The equations for the mechanical extraction were determined by measuring the pressure drop across the cloth and the pressure drop across the orifice in the experimental set-up (Figures 1 and 2).

The measurements were accomplished by placing a U-tube manometer across the flow orifice and across the cloth and recording the pressure drop versus time. The mass of water liquid was also recorded versus time for different initial pressure drops across the cloth. Two techniques were used in recording these quantities. First, because of the rapid change in pressure drop with time, the pressure drop across the orifice and across the cloth were recorded versus time, and then plotted versus each other eliminating the time (Graph 5). Secondly, it was found in recording the change in the mass of water liquid that the amount of water that could be removed by mechanical extraction was affected by removing the cloth from the system, weighing it, and replacing it. In order to remove this error, the cloth was removed after a given time and weighed. Then it was resoaked in water, and placed in the system with the same pressure drop for a different time period. In this way it was possible to obtain the results as plotted in Graphs 1 - 4.

The following equations were then determined from the graphs:

1. Graphs 1, 2, and 3

$$M_{WL} = M_{WLI}\, e^{-.0065 P_{CI} T} \text{, whenever } M_{WL}/M_{WLI} > C$$

M_{WL} = mass of water liquid in the cloth

M_{WLI} = initial mass of water liquid in the cloth

P_{CL} = initial pressure drop across the cloth

Defining this equation in terms of one-second intervals

$$M_{WL2} = M_{WLI}\, e^{-.0065 P_{CI}}$$

2. Graph 4

$$C = e^{-.0222 P_{CI}}$$

3. Graph 5

$$P_O = P_{OF} * (1.35 - P_C/P_{CI})$$

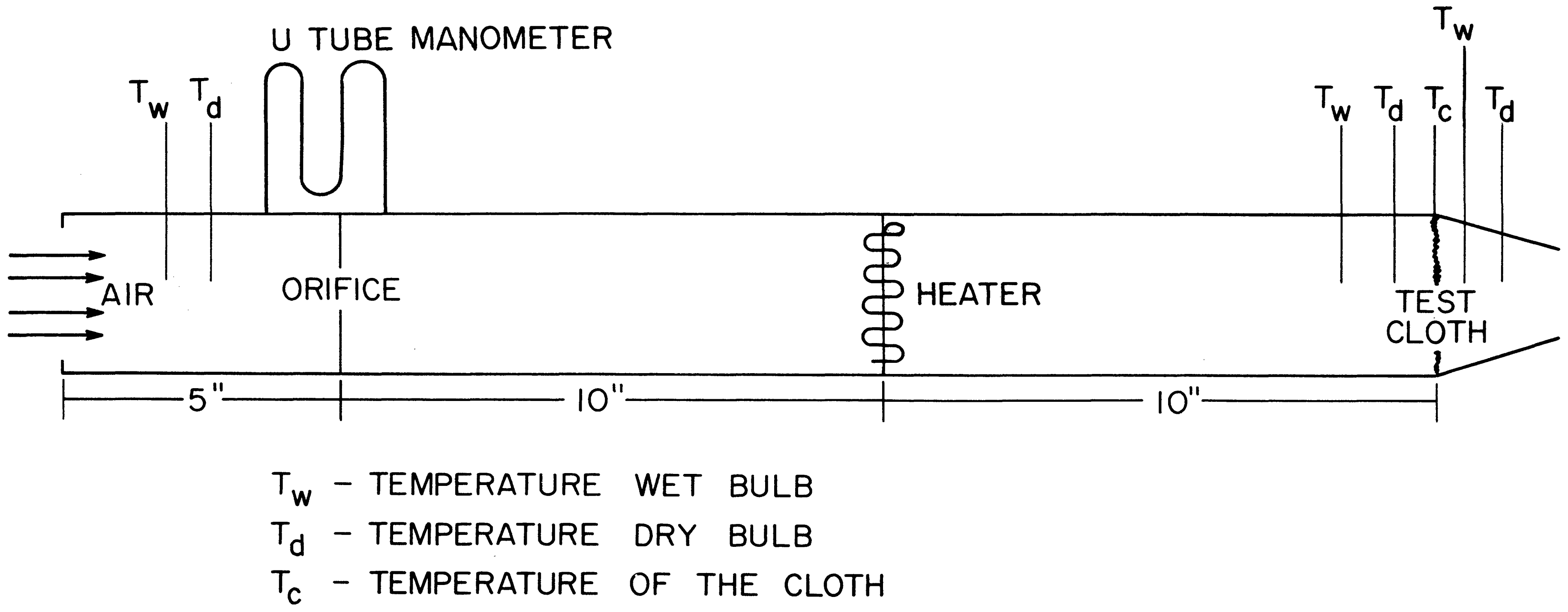
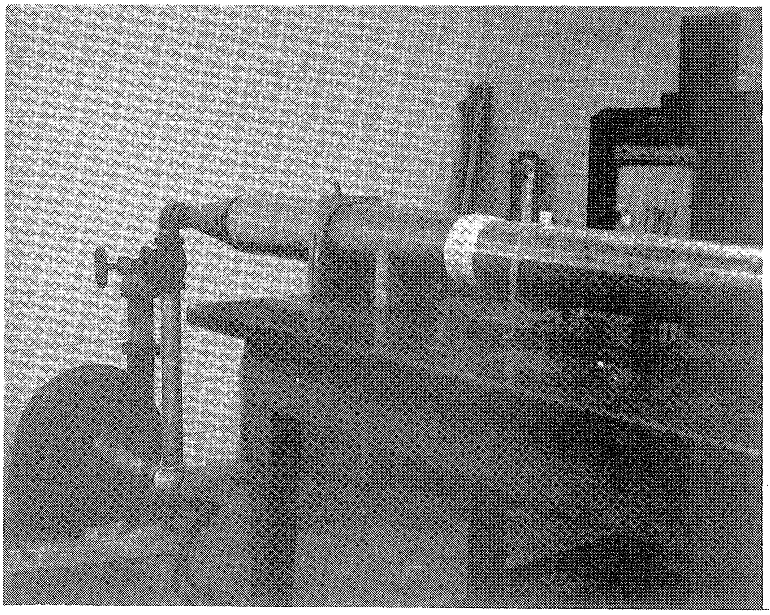
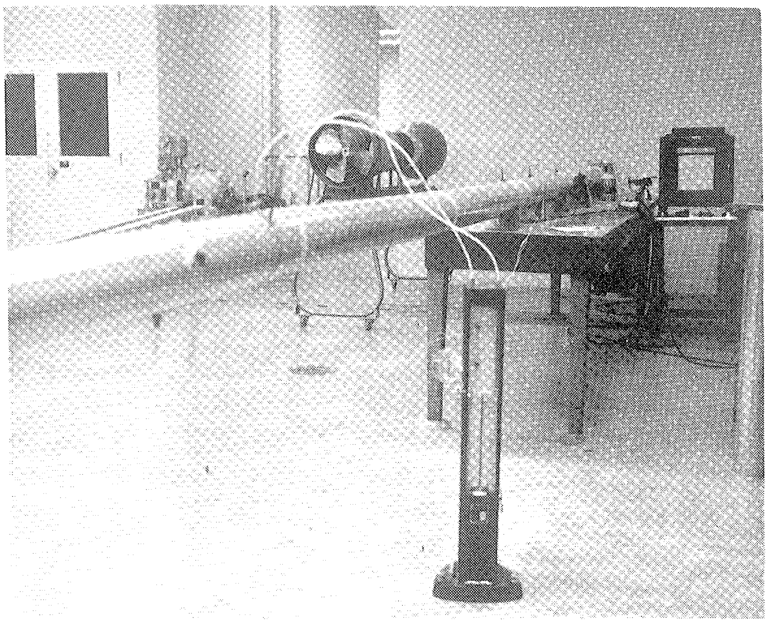


Figure 1. Test equipment.



Experimental
Set-up
Single Piece
of Cloth



Experimental
Set-up
Machine

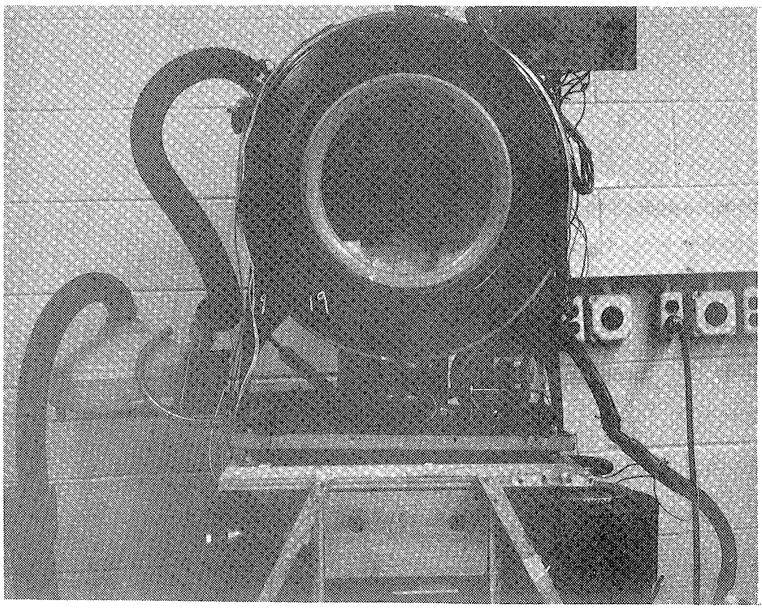


Figure 2

P_O = pressure drop across the orifice at time T

P_{OF} = maximum pressure drop across the orifice

P_C = pressure drop acorss the cloth at time T

P_{CI} = initial pressure drop across the cloth

Defining this equation in terms of the velocity of the incoming air

$$V_{AI} = V_{AIF}\sqrt{1.35 - P_C/P_{CI}}$$

V_{AI} = velocity of the air entering at time T

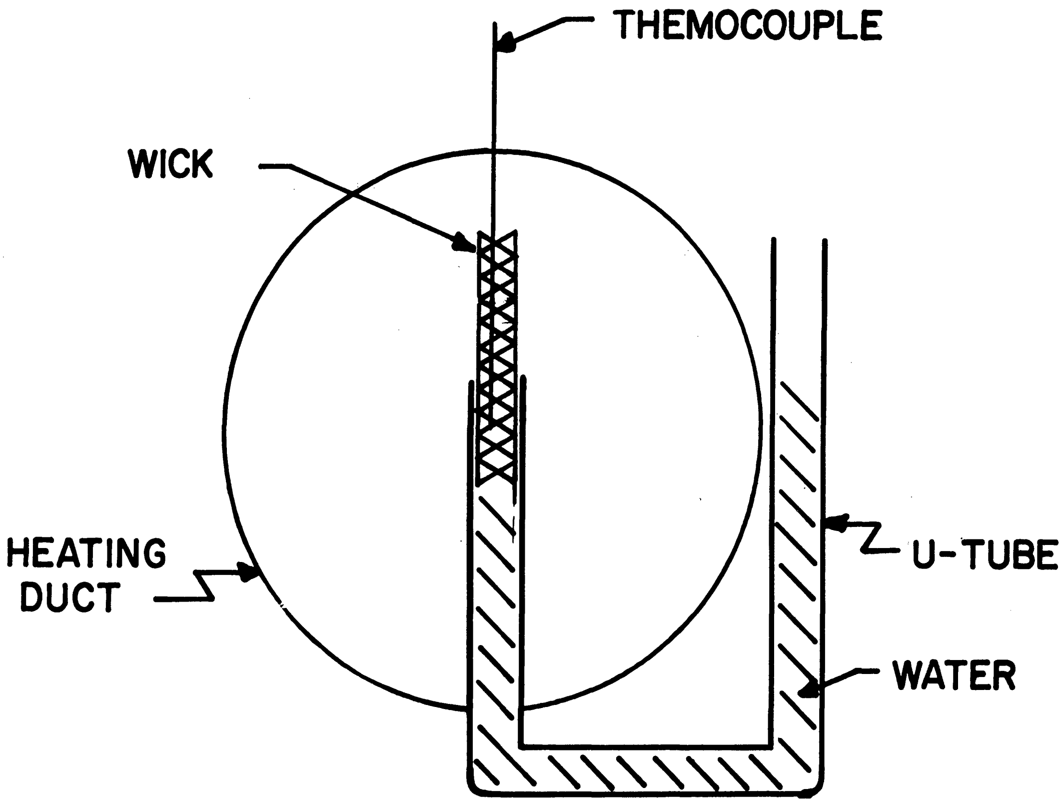
V_{AIF} = final velocity of the air entering

B. HEAT AND MASS TRANSFER COEFFICIENTS

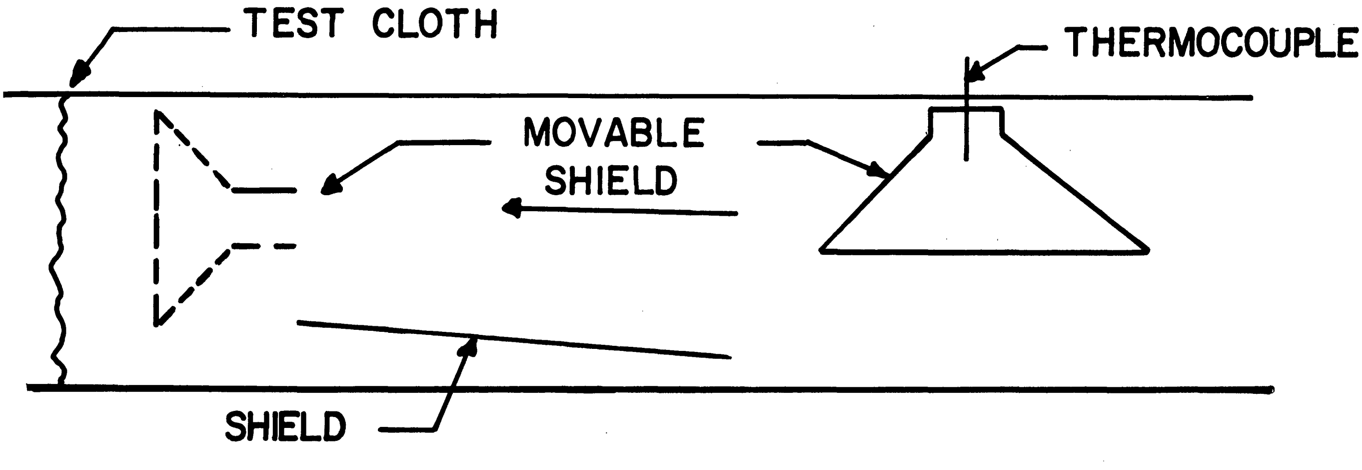
The experimental set-up for measuring the heat transfer coefficient, mass transfer coefficient, and drying times to check the validity of the computer program simulation of the drying process for a single piece of cloth is shown in Figures 1 and 2. The tube was made of six-inch diameter galvanized heating duct, twenty-five feet long. The length of the tube was necessary to provide for uniform flow through the orifice and uniform mixing of the heated air approaching the test cloth. The temperature measurements were made with thermocouples, and recorded versus time. The following quantities were measured:

1. The wet and dry bulb temperatures of the inlet air (T_{WI},T_{DI})
2. The wet and dry bulb temperatures of the heated air (T_{WH},T_{DH})
3. The wet and dry bulb temperatures of the exiting air (T_{WE},T_{DE})
4. The temperature of the cloth (T_C)
5. The pressure change across the orifice (P)

The wet bulb temperatures and the dry bulb temperatures at the exit were difficult to obtain. The wet bulb temperatures created a problem since they dried while the cloth was drying. The system that gave repeatable results was using a U-tube as a reservoir for the wet bulb and a cigarette lighter wick for the bulb.



In measuring the dry bulb temperature, a shield had to be made for the thermocouple since it became wet from the droplets removed from the cloth during mechanical extraction. The type of shields that were used are shown below:



The movable shield for the thermocouple was used because it was found to give the most repeatable results.

When these quantities were plotted versus time, the following input variables to the computer program were calculated.

1. Volume flow rate of air

$$Q = A_0 0 \sqrt{2G_C P/\rho}$$

A_0 = area of the orifice

C = coefficient of discharge

ρ = density of the air

2. The mass transfer coefficient (H_{MTX})

$$H_{MTX} = M_{WVT}\dot{M}_{AI}/(P_S - P_V)$$

M_{WVT} = mass of water vapor transported from the cloth. This is obtained by using the psychrometric chart, $T_{HW}, T_{HD}, T_{EW}, T_{ED}$, to obtain the difference in the amount of water per pound of dry air in front of and behind the test cloth.

$\dot{M}_{AI}$ = mass flow rate of air entering

P_S = saturated pressure at the temperature of the cloth (obtained from T_C)

P = vapor pressure of the heated air (obtained from T_{HD}, T_{HW})

From Graphs 6, 7, and 8, the following results were obtained:

$T_C = 53$

$T_{AI} = 76$

$T_{AVE} = 66$

$T_{AE} = 56$

$M_{WVT} = .0042$

$P_S = .1990$

$P_V = .0849$

$A_{CL} = .196$

$H_{MTX}/M_{AI} = .00132$

3. Heat transfer coefficient (H_{HTX})

Using the assumptions discussed in the computer program section:

$$\dot{Q}_{AC} = A_{CL}H_{HTX}(T_{AVE} - T_C)$$

$\dot{Q}_{AC}$ = heat transfer rate from the air to the cloth

$T_{AVE} = 1/2\ (T_{DH} + T_{DE})$

A_{CL} = area of the cloth

$$Q_{AC} = (C_C M_C T_C + H_F M_{WL} + H_F M_{WL}) + M_{WL}(H_V - H_F)$$

C_C = specific heat of the cloth

M_C = mass of the cloth

H_V = enthalpy of the water vapor per pound mass at the temperature of the cloth

H_F = enthalpy of the liquid water per pound mass at the temperature of the cloth

$$H_{HTX} = (C_C M_C T_C + H_F M_{WL} + H_F M_{WL} + M_{WL}(H_V - H_F))/(T_{AVE} - T_C)A_{CL}$$

From Graphs 6, 7, and 8, the following results were obtained:

$T_C = 53$

$T_{AI} = 76$

$T_{AVE} = 66$

$T_{AE} = 56$

$M_{WVT} = .0042$ See mass transfer coefficient

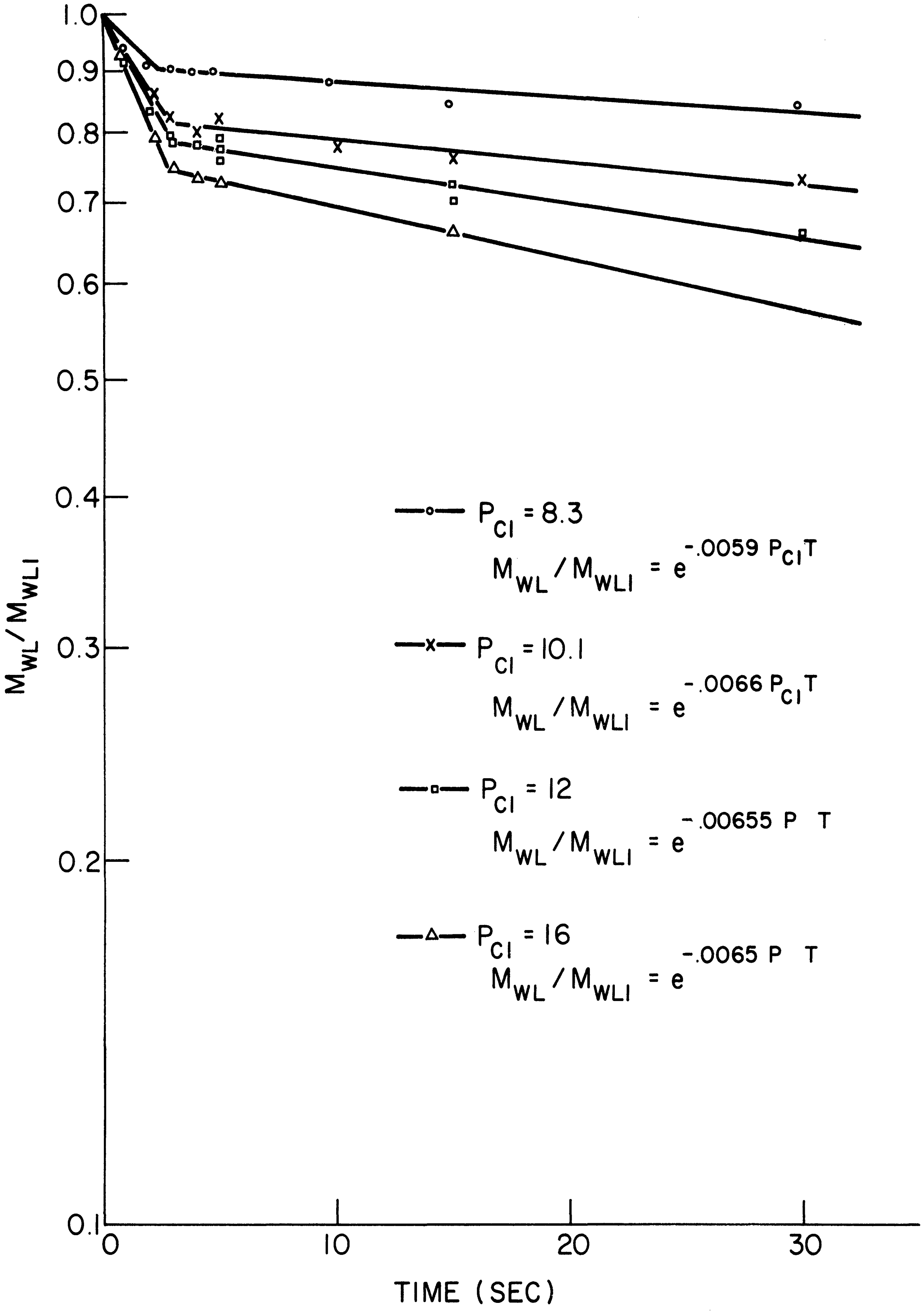
$T_C = 0$

$A_{CL} = .196$

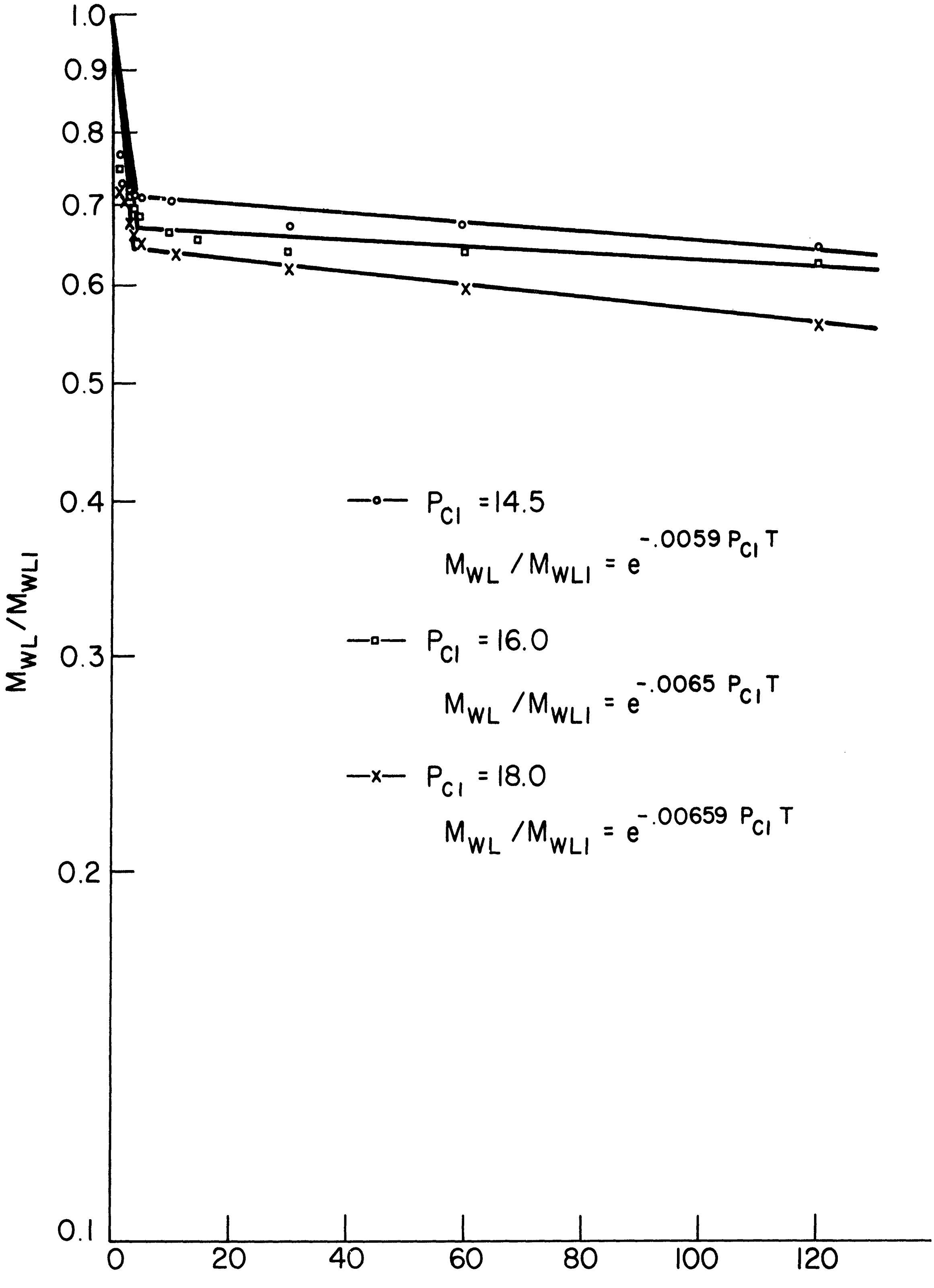
$H_{HTX}/M_{AI} = 1.79$

APPENDIX A

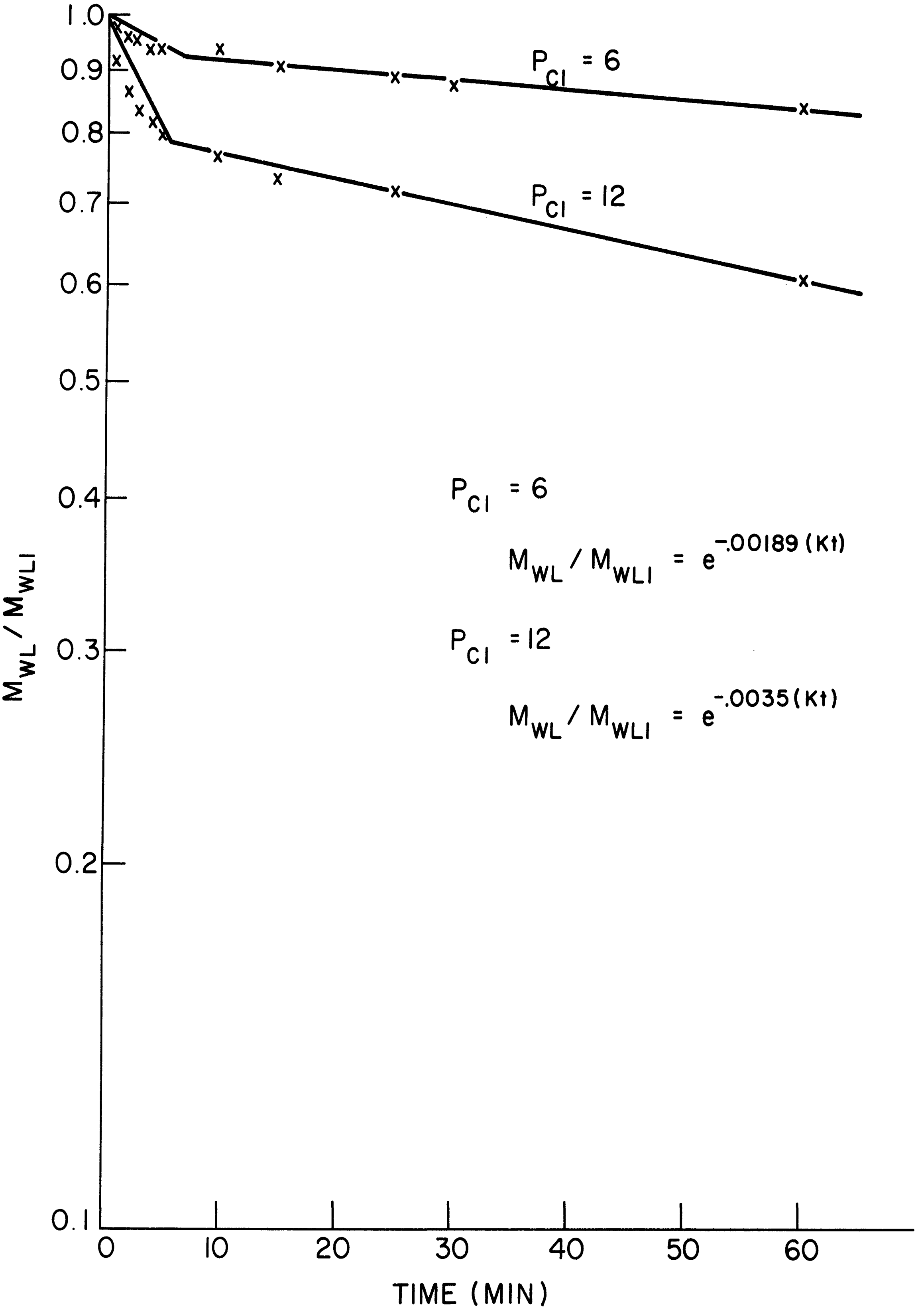
GRAPHS 1 - 8



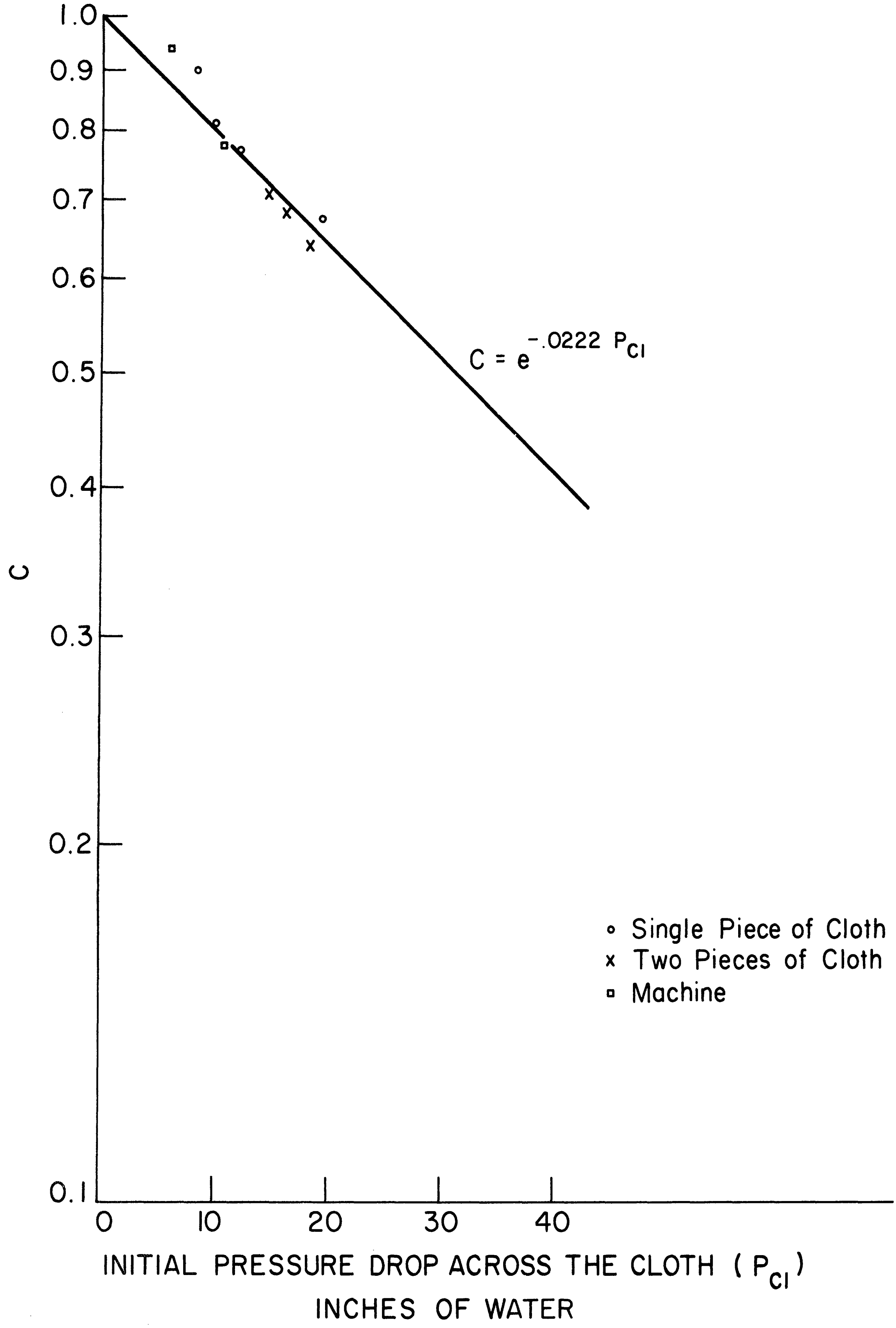
Graph 1. Single piece of cloth $\left(\frac{\text{Mass of water in cloth}}{\text{Initial mass of water in cloth}} \text{ vs. time}\right)$



Graph 2. Two pieces of cloth $\left(\frac{\text{Mass of water in cloth}}{\text{Initial mass of water in cloth}} \text{ vs. time}\right)$.

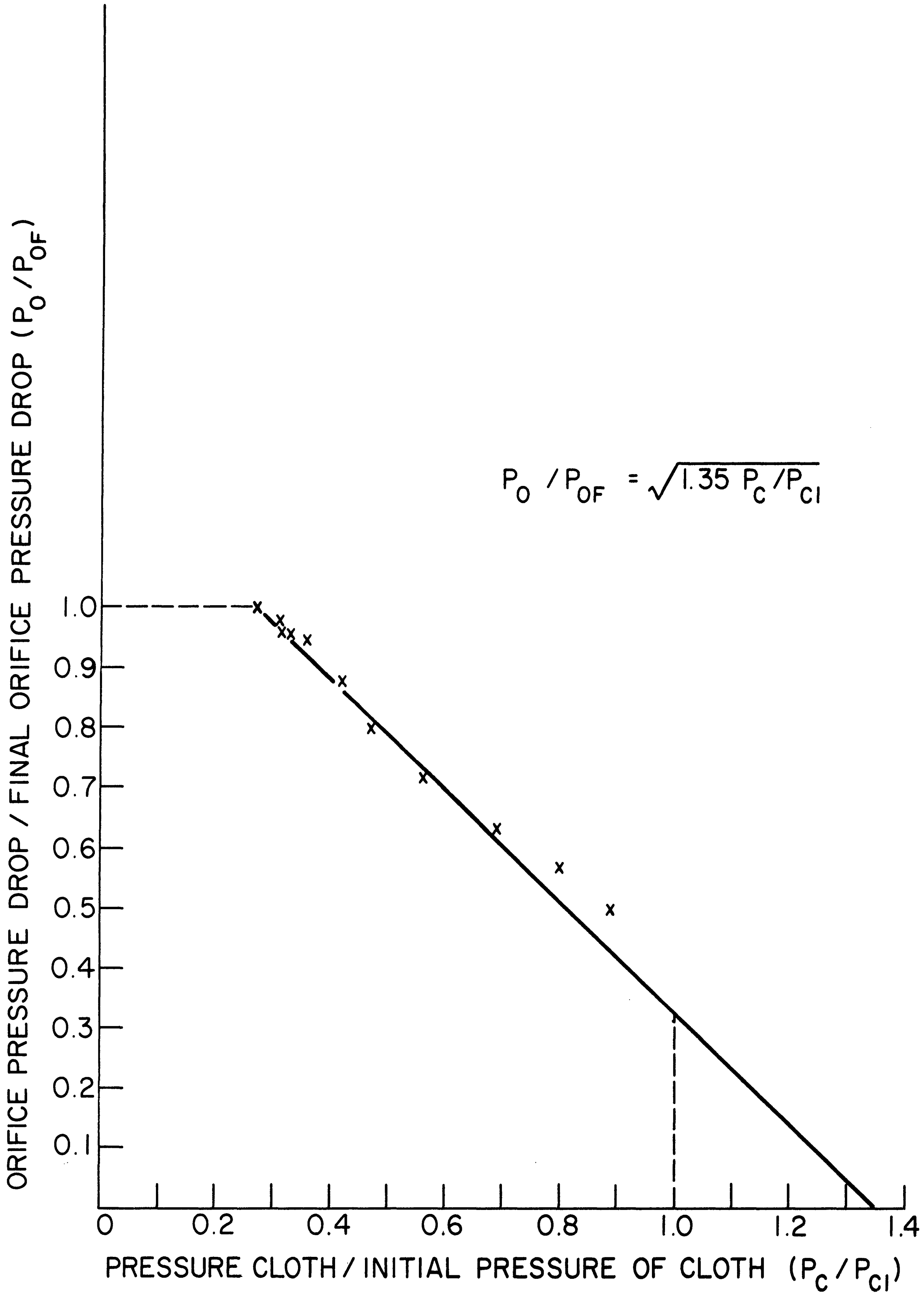


Graph 3. Machine $\left(\frac{\text{Mass of water in clothes}}{\text{Initial mass of water in clothes}} \text{ vs. time}\right)$.

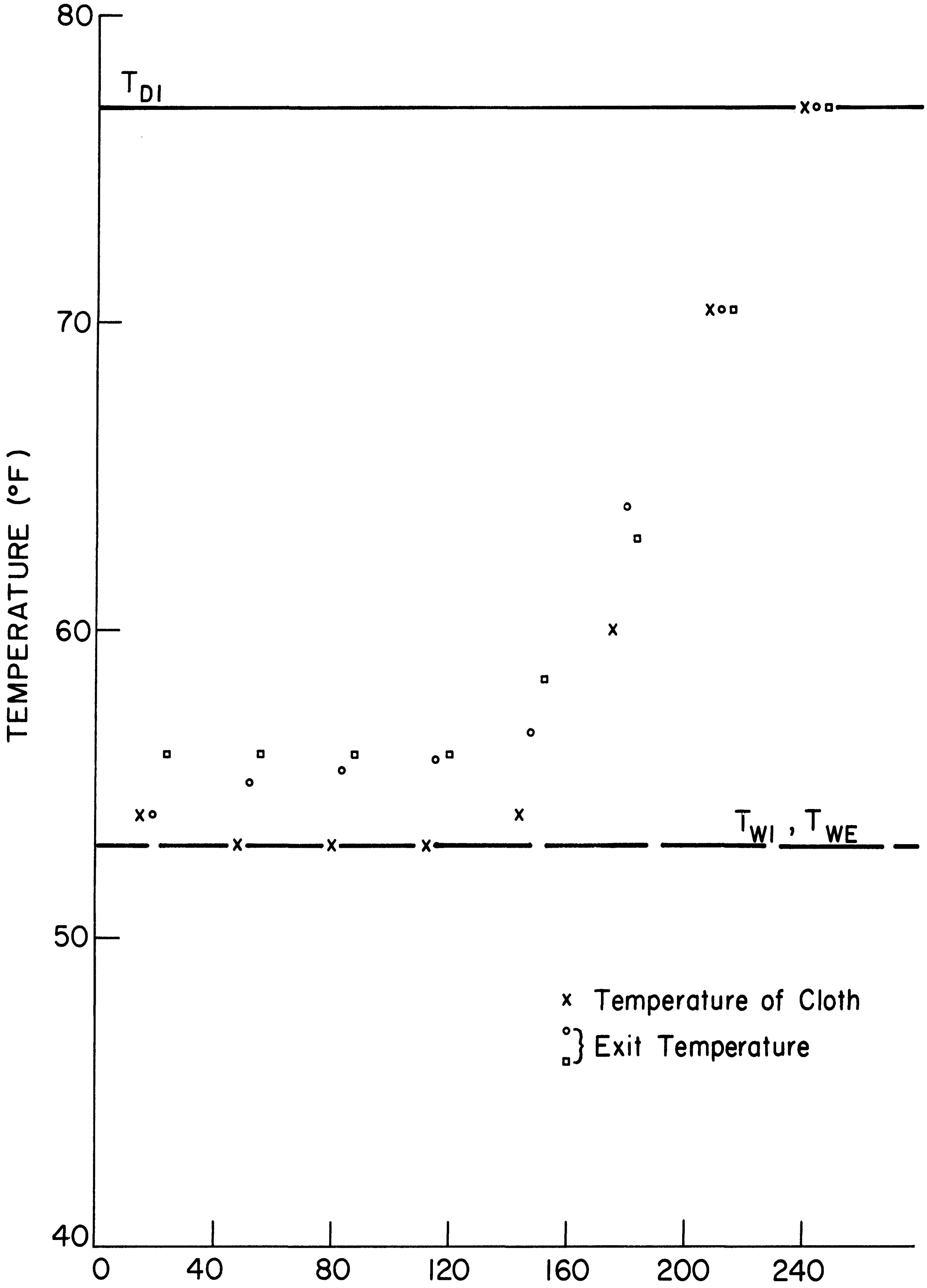


Graph 4. End of mechanical extraction - C.

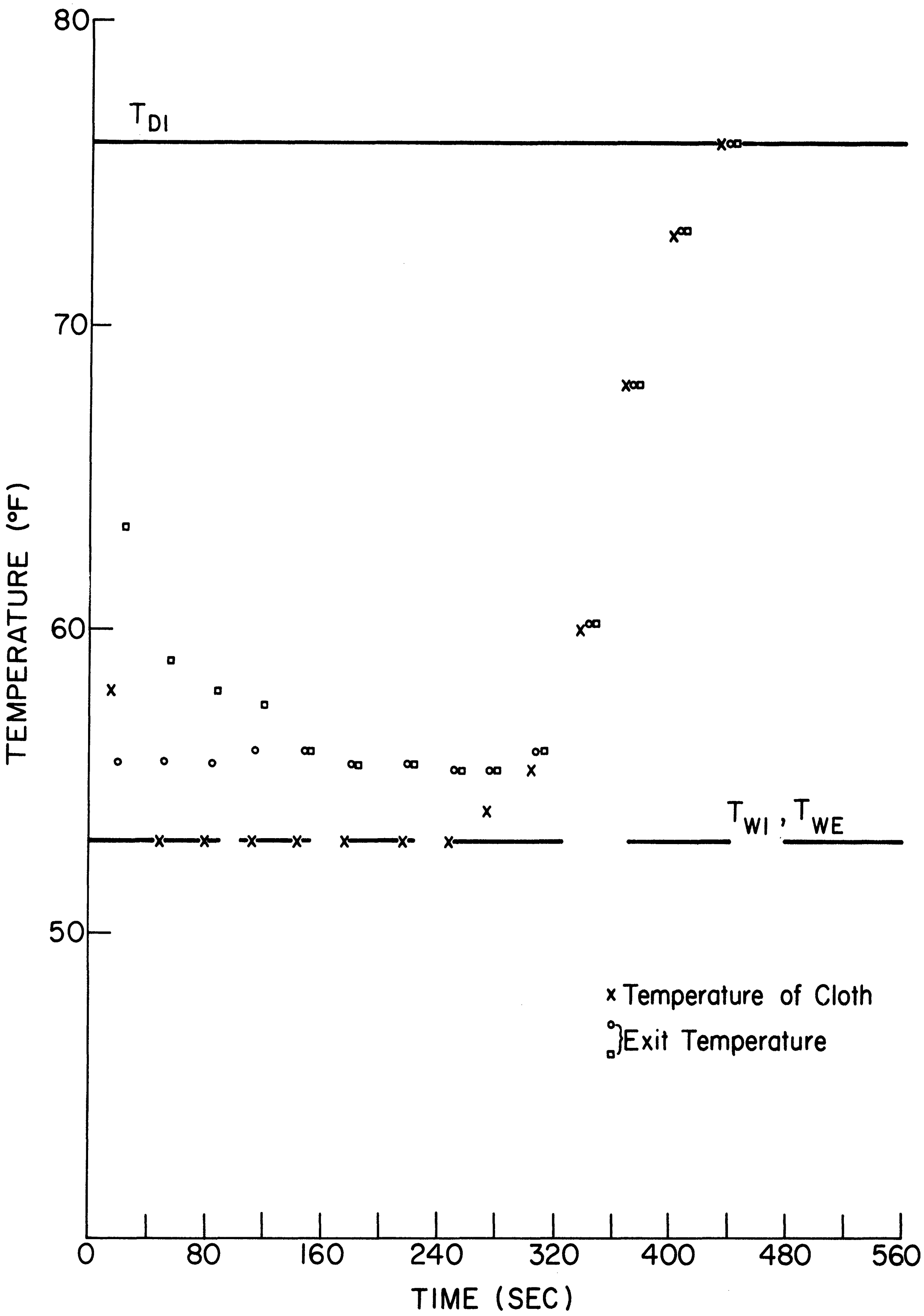
$$C = \frac{\text{Mass of water in cloth}}{\text{Initial mass of water in cloth}} \text{ vs. time}$$



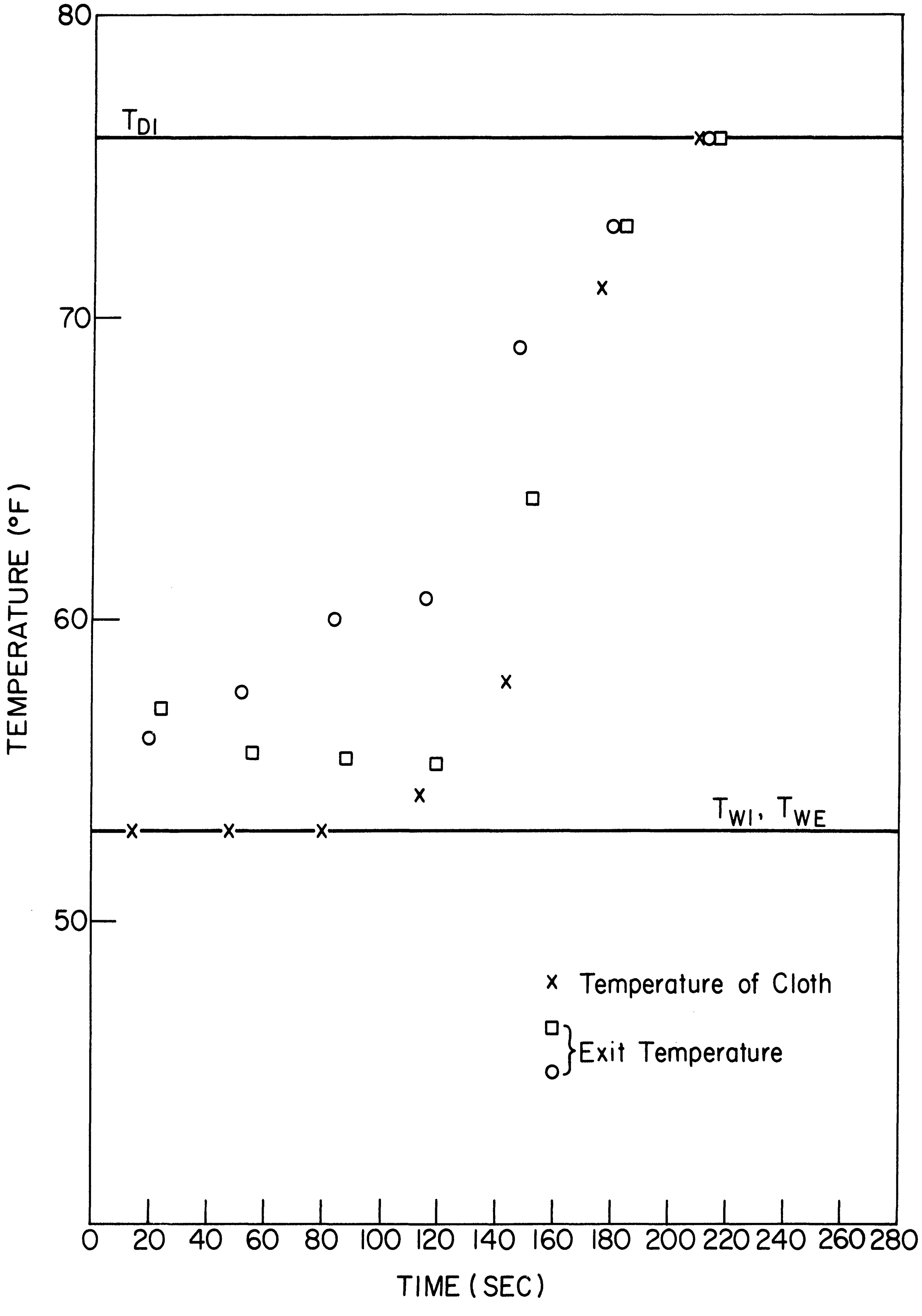
Graph 5. $\dfrac{\text{Pressure drop across the orifice}}{\text{Final pressure drop across the flow orifice}}$ vs. $\dfrac{\text{Pressure drop across the cloth}}{\text{Initial pressure drop across the cloth}}$



Graph 6. Temperature of cloth (inlet and outlet air vs. time).



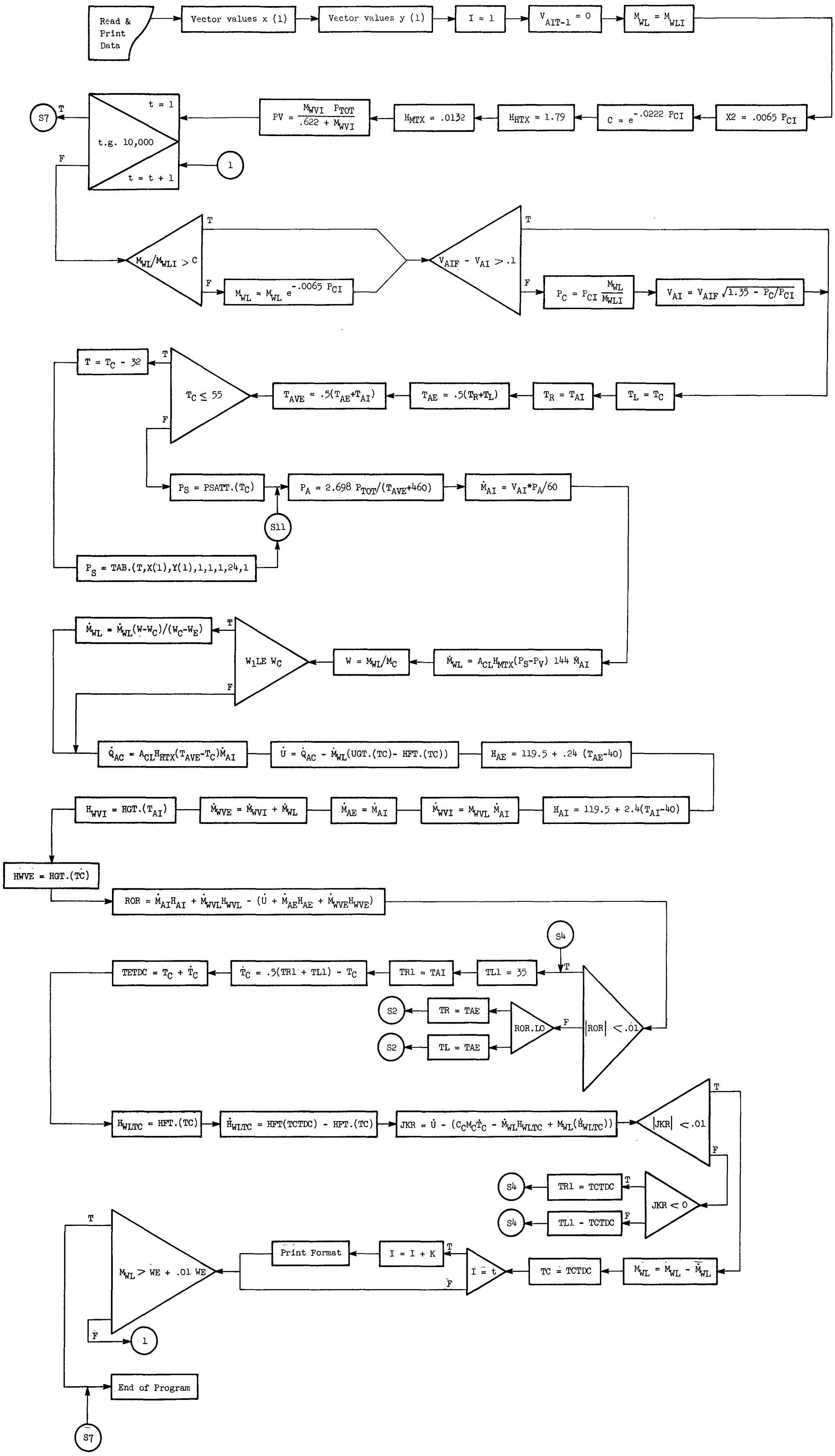
Graph 7. Temperature of cloth (inlet and outlet air vs. time).



Graph 8. Temperature of cloth (inlet and outlet air vs. time).

APPENDIX B

FLOW DIAGRAM AND PROGRAM LISTINGS


Read & Print Data
Vector values x (1)
Vector values y (1)
I = 1
$V_{AIT-1} = 0$
$M_{WL} = M_{WLI}$
$X2 = .0065\ P_{CI}$
$C = e^{-.0222\ P_{CI}}$
$H_{HTX} = 1.79$
$H_{MTX} = .0132$
$PV = \frac{M_{WVI}\ P_{TOT}}{.622 + M_{WVI}}$
t = 1
t.g. 10,000
t = t + 1
S7
T
F
1
$M_{WL}/M_{WLI} > C$
T
F
$M_{WL} = M_{WL}\ e^{-.0065\ P_{CI}}$
$V_{AIF} - V_{AI} > .1$
T
F
$P_C = P_{CI}\ \frac{M_{WL}}{M_{WLI}}$
$V_{AI} = V_{AIF}\sqrt{1.35 - P_C/P_{CI}}$
$T_L = T_C$
$T_R = T_{AI}$
$T_{AE} = .5(T_R+T_L)$
$T_{AVE} = .5(T_{AE}+T_{AI})$
$T_C \leq 55$
T
F
$T = T_C - 32$
$P_S = PSATT.(T_C)$
$P_A = 2.698\ P_{TOT}/(T_{AVE}+460)$
$\dot{M}_{AI} = V_{AI}{*}P_A/60$
S11
$P_S = TAB.(T,X(1),Y(1),1,1,1,24,1$
$\dot{M}_{WL} = A_{CL}H_{MTX}(P_S-P_V)\ 144\ \dot{M}_{AI}$
$W = M_{WL}/M_C$
$W_1 LE\ W_C$
T
F
$\dot{M}_{WL} = \dot{M}_{WL}(W-W_C)/(W_C-W_E)$
$\dot{Q}_{AC} = A_{CL}H_{HTX}(T_{AVE}-T_C)\dot{M}_{AI}$
$\dot{U} = \dot{Q}_{AC} - \dot{M}_{WL}(UGT.(TC)- HFT.(TC))$
$H_{AE} = 119.5 + .24\ (T_{AE}-40)$
$H_{AI} = 119.5 + 2.4(T_{AI}-40)$
$\dot{M}_{WVI} = M_{WVL}\ \dot{M}_{AI}$
$\dot{M}_{AE} = \dot{M}_{AI}$
$\dot{M}_{WVE} = \dot{M}_{WVI} + \dot{M}_{WL}$
$H_{WVI} = HGT.(T_{AI})$
HWVE = HGT.(TC)
$ROR = \dot{M}_{AI}H_{AI} + \dot{M}_{WVL}H_{WVL} - (\dot{U} + \dot{M}_{AE}H_{AE} + \dot{M}_{WVE}H_{WVE})$
S4
T
$|ROR| < .01$
F
ROR.LO
TR = TAE
TL = TAE
S2
S2
TL1 = 35
TR1 = TAI
$\dot{T}_C = .5(TR1 + TL1) - T_C$
$TETDC = T_C + \dot{T}_C$
$H_{WLTC} = HFT.(TC)$
$\dot{H}_{WLTC} = HFT(TCTDC) - HFT.(TC)$
$JKR = \dot{U} - (C_C M_C \dot{T}_C - \dot{M}_{WL}H_{WLTC} + M_{WL}(\dot{H}_{WLTC}))$
$|JKR| < .01$
T
F
JKR < 0
T
F
TR1 = TCTDC
TL1 - TCTDC
S4
S4
$M_{WL} = M_{WL} - \dot{M}_{WL}$
TC = TCTDC
I = t
T
F
I = I + K
Print Format
$M_{WL} > WE + .01\ WE$
T
F
1
End of Program
S7

SINGLE PIECE OF CLOTH PROGRAM

```
          READ AND PRINT DATA
          VECTOR VALUES X(1)=1.,2.,3.,4.,5.,6.,7.,8.,9.,10.,11.,12.,
        9 13.,14.,15.,16.,17.,18.,19.,20.,21.,22.,23.,24.
          VECTOR VALUES Y(1)=.0886,.0921,.0961,.1001,.1041,.1082,.1126
        9 ,.1171,.1217,.1260,.1315,.1367,.1420,.1483,.1532,.1593,
        9 .1652,.1716,.1780,.1845,.1918,.2037,.2063,.2130
          INTEGER TIME,PTIME,I
          PRINT COMMENT$TIME   MWL      PC          VAI      TC       TAE
        9   TAVE$
          I=1
          VAI =0.
          C= 2.71828.P.(-.0222*PCI)
          MWL=MWLI
          X2=.0065*PCI
          HHTX=1.79
          HMTX=.00132
          PV=MWVI*TOTPA/(.622+MWVI)
         .THROUGH S1, FOR TIME =1,1,TIME .G.10000
         2.WHENEVER MWL/MWLI.G.C
         3.MWL=MWL*(2.71828.P.(-X2))
         4.END OF CONDITIONAL
S12       WHENEVER VAIF-VAI .G..1
            PC=PCI*MWL/MWLI
          VAI=VAIF*((1.35-PC/PCI).P..5)
          END OF CONDITIONAL
          TL=TC
          TR=TAI
S2        TAE = .5*(TR+TL)
          TAVE =.5* (TAI+TAE)
          WHENEVER TC .LE.35,TRANSFER TO S7
          WHENEVER TC .LE.55.
            T=TC-32.
            PS=TAB.(T,X(1),Y(1),1,1,1,24,1)
          TRANSFER TO S11
            END OF CONDITIONAL
          PS=PSATT.(TC)
S11       ARHO=2.698*TOTPA/(TAVE+460.)
          MDAI=VAI*ARHO/60.
          QDAC=ACL*HHTX*(TAVE-TC)*MDAI
          MDWL=ACL*HMTX*(PS-PV)*144*MDAI
          W=MWL/MC
          WHENEVER W .LE. WC,MDWL =MDWL *(W-WE)/(WC-WE)
          HVTC=HGT.(TC)
          HLTC=HFT.(TC)
          UD=QDAC-MDWL *(HVTC-HLTC)
          HAI=119.5+.24*(TAI-40.)
          HAE=119.5+.24*(TAE-40.)
          MDWVI=MWVI*MDAI
          MDAE=MDAI
          MDWVE=MDWVI+MDWL
          HWVE= HGT.(TAE)
          HWVI=HGT.(TAI)
          ROR=MDAI*HAI+MDWVI*HWVI-(UD+MDAE*HAE+MDWVE*HWVE)
```

correction to make program results fit data at point C.

1. WHENEVER MWL/MWLI .LE. C, TRANSFER to S12

6. WHENEVER MWL/MWLI .L. C, MWL=MWLI* C

```
             WHENEVER .ABS. ROR .L..1 , TRANSFER TO S3
             WHENEVER ROR .L.O.
               TR=TAE
               TRANSFER TO S2
             OTHERWISE
               TL=TAE
               TRANSFER TO S2
             END OF CONDITIONAL
    S3       TL1= 35.
             TR1=TAI
    S4       TDC= .5*(TR1+TL1)- TC
             TCTDC=TC+TDC
             HWLTC = HFT.(TC)
             HDWLTC=HFT.(TCTDC)-HFT.(TC)
             JKR = (UD-(CC*MC*TDC-MDWL*HWLTC+HDWLTC*MWL))
             WHENEVER .ABS. JKR .L..1 ,TRANSFER TO S6
             WHENEVER JKR.L.O .
             TR1=TCTDC
             OTHERWISE
               TL1=TCTDC
             END OF CONDITIONAL
             TRANSFER TO S4
    S6       MWL=MWL-MDWL
             TC=TCTDC
             WHENEVER I .E. TIME
             PRINT FORMAT$1H ,I4,6F8.4 *$,TIME,MWL,PC,VAI,TC,TAE,TAVE
             I=I+PTIME
             END OF CONDITIONAL
             WHENEVER W .LE. WE+.01*WE,TRANSFER TO S7
    S1       CONTINUE
             PRINT COMMENT $ TIME GREATER THAN 1000 $
    S7       END OF PROGRAM
```

MACHINE PROGRAM

```
             READ AND PRINT DATA
             VECTOR VALUES X(1)=1.,2.,3.,4.,5.,6.,7.,8.,9.,10.,11.,12.,
           9 13.,14.,15.,16.,17.,18.,19.,20.,21.,22.,23.,24.
             VECTOR VALUES Y(1)=.0886,.0921,.0961,.1001,.1041,.1082,.1126
           9 ,.1171,.1217,.1260,.1315,.1367,.1420,.1483,.1532,.1593,
           9 .1652,.1716,.1780,.1845,.1918,.2037,.2063,.2130
             INTEGER TIME,PTIME,I
             PRINT COMMENT$TIME    MWL      PC          VAI      TC        TAE
           9   TAVE$
             I=1
             VAI=0.
             C= 2.71828.P.(-.0222*PCI)
             X2=.39*PCI*K
             MWL=MWLI
             HHTX=2.02
             HMTX=.00132
             PV=MWVI*TOTPA/(.622+MWVI)
             THROUGH S1,FOR TIME=1,1,TIME.G.10000
             MWLN=MWL*MCN/MC*60.*K
             WHENEVER MWL/MWLI .G.C
             MDWLN=MWLN*(1-2.71828.P.(-X2))
             MWL=MWL-MDWLN
              END OF CONDITIONAL
             WHENEVER VAIF-VAI .G..1
               PC=PCI*MWL/MWLI
             VAI=VAIF*((1.35-PC/PCI).P..5)
             END OF CONDITIONAL
             TL=TC
             TR=TAI
S2           TAE=.5*(TR+TL)
             TAVE=.5*(TAI+TAE)
             WHENEVER TC .LE.35,TRANSFER TO S7
             WHENEVER TC .LE. 55.
               T=TC-32.
               PS=TAB.(T,X(1),Y(1),1,1,1,24,1)
               TRANSFER TO S11
               END OF CONDITIONAL
             PS=PSATT.(TC)
S11          ARHO=2.698*TOTPA/(TAVE+460.)
             MDAI=VAI*ARHO
             QDAC=ACL*HHTX*(TAVE-TC)*MDAI*K1*K
             MDWLN=ACL*HMTX*(PS-PV)*144*MDAI*K1*K
             W=MWL/MC
             WHENEVER W .LE. WC,MDWLN=MDWLN*(W-WE)/(WC-WE)
             HLTC=HFT.(TC)
             HVTC=HGT.(TC)
             UD=QDAC-MDWLN*(HVTC-HLTC)
             HAI=119.5+.24*(TAI-40.)
             HAE=119.5+.24*(TAE-40.)
             MDWVI=MWVI*MDAI
             MDAE=MDAI
             MDWVE=MDWVI+MDWLN
             HWVI=HGT.(TAI)
```

```
              HWVE= HGT.(TAE)
              ROR=MDAI*HAI+MDWVI*HWVI-(UD+MDAE*HAE+MDWVE*HWVE)
              WHENEVER .ABS. ROR .L. .1, TRANSFER TO S3
              WHENEVER ROR .L.0.
                TR=TAE
                TRANSFER TO S2
              OTHERWISE
                TL=TAE
                TRANSFER TO S2
              END OF CONDITIONAL
  S3          TL1= 35.
              TR1=TAI
  S4          TDC= .5*(TR1+TL1)- TC
              TCTDC=TC+TDC
              HWLTC = HFT.(TC)
              HDWLTC=HFT.(TCTDC)-HFT.(TC)
              JKR=(UD-(CC*MC*TDC-MDWLN*HWLTC+HDWLTC*MWL))
              WHENEVER .ABS. JKR .L. .1,TRANSFER TO S6
              WHENEVER JKR.L.0 .
              TR1=TCTDC
              OTHERWISE
                TL1=TCTDC
              END OF CONDITIONAL
              TRANSFER TO S4
  S6          MWL=MWL-MDWLN
              TC=TCTDC
              WHENEVER I .E. TIME
              PRINT FORMAT$1H ,I4,6F8.4 *$,TIME,MWL,PC,VAI,TC,TAE,TAVE
              I=I+PTIME
              END OF CONDITIONAL
              WHENEVER W .LE. WE+.01*WE,TRANSFER TO S7
  S1          CONTINUE
              PRINT COMMENT $ TIME GREATER THAN 1000 $
  S7          END OF PROGRAM
```

APPENDIX C

COMPUTER PROGRAM NOMENCLATURE

SINGLE PIECE OF CLOTH

ACL - area of the cloth

ARHO - density of the air at temperature TAVE

C - the limit on the mass of water that can be removed mechanical extraction

CC - specific heat of the cloth

HAE - enthalpy of the air at the exit temperature

HAI - enthalpy of the air at the inlet temperature

HHTX - heat transfer coefficient of the cloth

HMTX - mass transfer coefficient of the cloth

HLTC
HWLTC - enthalpy of the water liquid in the cloth at the temperature of the cloth

HVTC - enthalpy of the water vapor in the cloth at the temperature of the cloth

HDWLTC - change in the enthalpy of the water liquid in the cloth due to the change in the temperature of the cloth

HWVE - enthalpy of the water vapor at the exit temperature

HWVI - enthalpy of the water vapor at the inlet temperature

MC - mass of the cloth

MDAE - mass flow rate of air at the exit

MDAI - mass flow rate of air at the inlet

MDWL - change in the mass of water liquid in the cloth

MWL - mass of water liquid in the cloth

PC - pressure drop across the cloth

PCI - initial pressure drop across the cloth

PTIME - time between the output printout

PS - saturation pressure at the temperature of the cloth

PV - vapor pressure of the water vapor at TAVE

QDAC - heat transver rate to the cloth

TAB.( ) - external function to interpolate the values of PS for temperatures below 55°

TC - temperature of the cloth

TDC - change in the temperature of the cloth

TCTDC - TC + TDC

TAI - inlet temperature of the air

TAE - exit temperature of the air

TAVE - average temperature of the air across the cloth

TOTPA - the total pressure of the air and water vapor

TL,TR,TLI,TRI - limits for the iterations to find TAVE and TDC

UD - change in the internal energy of the cloth, water, and water vapor

W - ratio of the mass of water liquid to the mass of the cloth

WC - critical ratio W

WE - the ratio of W where the water in the cloth is in equilibrium with the water vapor in the air

VAI - volume flow rate of air

VAIF - final volume flow rate of air

MACHINE

MWLN - mass of water liquid at the nozzle

MDWLN - change in the mass of water liquid at the nozzle

MCN - mass of cloth at the nozzle

K - percentage of time that the cloth covers the nozzle

KI - the average number of thicknesses of cloth that cover the nozzle

STEAM TABLES EXTERNAL FUNCTION

HGT.(T) - enthalpy of saturated water vapor at temperature T

HFT.(T) - enthalpy of saturated water liquid at temperature T

PSATT.(T) - saturation pressure of water at temperature T